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Supporting developer-onboarding with enhanced resource finding and visual exploration

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SUPPORTING DEVELOPER-ONBOARDING WITH ENHANCED RESOURCE FINDING AND VISUAL EXPLORATION

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Understanding the basic structure of a code base and a development team are essential to get new developers up to speed in a software development project. Developers do so through the process of early experimentation with code and the creation of mental models of technical and social structures in a project. However, getting up-to-speed in a new project can be challenging due to difficulties in: finding the right place to begin explorations, expanding the focus to determine relevant resources for tasks, and identifying dependencies across project elements to gain a high-level overview of project structures. In this thesis, I first identified six challenges that developers face during the process of developer onboarding from recent research studies and informal interviews with developers. To address these challenges, I implemented automated tool support with enhanced resource finding and visual exploration. Specifically, I proposed six functional requirements for supporting developers onboarding. I then extended the project tool Tesseract to support these functionalities to help novice developers find relevant resources (files, developers, bugs, etc.) and understand project structures when joining a new project. To understand how the onboarding functionalities work in supporting developers' onboarding process, I conducted a user study with typical onboarding tasks requiring early experimentation and internalizing project structures. The results indicated that enhanced search features, the ability to explore semantic relationships across repositories, and network-centric visualizations of project structures were very effective in supporting onboarding.

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Chapter 1

Introduction

Software systems may be composed of a large code base with thousands or millions of lines of code and complex interdependencies, understanding which is critical for developers to contribute to or maintain a software project. Getting familiar with the basic structure of a code base is especially essential for new developers to get up to speed in a software development project and start contributing. The process of becoming proficient with a code base is known as developer-onboarding [10]. The concept of onboarding is originally from management science, dealing with the process that new employees use to learn the knowledge, skills, and behaviors that they need to succeed in their new organizations [3]. In software development, onboarding (sometimes referred to as a joining script [43]) helps new developers learn about a software engineering project and become members of the development team.

Developer-onbarding has long been a focus of study in open source projects mainly because of its novel, volunteer-based business model and self-governing team structures [15, 43]. More recently, the study of developer-onboarding has been extended into the domain of commercial projects. Research results indicate that it is very likely for novice software developers to run into frustration with a number of factors: com-

munication, collaboration, technical difficulties, cognition, etc. [5]. It was found that experienced developers face challenges too when joining a new project, even when they move across projects within the same organization.

Primary factors which account for successful integration of developers into a project were identified by Dagenais et al. in their study of integration into a new software project landscape [12]. They found that the main factors that impact developers joining a software development project are early experimentation, internalizing structures and cultures, and progress validation [12]. *Early experimentation* refers to developers experimenting with the code base by performing small tasks to gain an understanding of the project [12]. It prepares newcomers to further explore and understand a complex project. *Internalizing structures and cultures* within the project refers to new developers efficiently identifying relevant resources and finding a place to fit themselves into the project [12]. Good *progress validation* allows managers and mentors of new developers to check if the new developers are on the right track and that they are not stuck on a small problem for long periods of time. Studies have found that new developers don't always know where to ask for help [12].

In this work, I focus on challenges in early experimentation and internalization of technical and social structures in the onboarding process of developers joining a new project landscape. Specifically, this work addresses the following challenges that hinder onboarding in early experimentation task and internalizing project structures.

First, it is nontrivial to accurately identify a good starting point in a software project and it is challenging for new developers to find the relevant resources needed to complete the starter tasks [34]. Second, the investigations of project resources are limited by the current search capability, which is mainly provided by "keyword-based" search [12]. Third, understanding the overall structures of a project and interrelationships between various resources are considered critical, but it is difficult

for new developers to obtain such information during the early stage of their onboarding process [34]. Fourth, project investigations currently have to be performed separately per repository, which makes it difficult for new developers to understand project dependencies across multiple repositories [38]. Further, the majority of software investigations treat the technical and social aspects of a project as dichotomous; whereas, studies have shown that understanding the social structure and culture is particularly important in getting assimilated into a project [12, 15]. Finally, large scale of software systems with millions of lines of code and hundreds of developers makes the creation of accurate mental models of the project cognitively challenging [38].

Currently, developers use a mix of technology (issue trackers, versioning systems), experimentation (getting their hands dirty by coding), and social means (seeking help from mentors, experienced developers) to perform tasks in early experimentation and for internalizing project structures [1, 5, 12]. Developers usually search for relevant information for a bug in bug systems like Bugzilla [8] or issue trackers like Trac [40]. They may look for commit history in versioning systems such as SVN [39] and Git [18]. Developers may use command line query as well as some web-based UIs of these tools. However, they have to query over different systems separately and then aggregate those results manually to get the information they want. Most of the time they have to build queries over the target database manually and repeat this step numerous times. This resource finding process incurs significant time cost due to inefficient queries and can be improved.

Studies have found that good mentoring is one of the most effective and irreplaceable factors in facilitating onboarding [16]. For example, in one study new developers needed frequent meetings with their mentors for up to four weeks, after which they could operate more or less independently with one or two meetings per

week [16]. However, such mentoring is not always cost effective or feasible (e.g., in open source or distributed development settings). In such situations, automated support for onboarding can be beneficial.

Developers onboarding a project also prefer visualizations to understand the code base and communicate with mentors or experienced teammates [10]. However, most of the time they have to draw diagrams on a whiteboard due to the poor tool support available for structural views of project resources and socio-technical dependencies [10]. In this case, visualizations of project resources may help developers understand a new project more easily.

To facilitate developer onboarding with automated support and provide visualizations of project resources, I first identify a set of functionality needs for onboarding based on a literature survey of developer onboarding and its challenges, informal interviews with some industry partners, and pilot studies. These functionalities include: (1) identification of relevant resources to aid early experimentation, (2) seamless investigation of data that is fragmented across multiple repositories, (3) investigation of semantic relationships, (4) exploration of social, technical, and socio-technical dependencies, (5) representation of high-level project structures, and (6) facilitating top-down and bottom-up comprehension strategies.

To achieve these onboarding functionalities, I extended a project exploration tool, Tesseract, and used it as a platform for evaluating these functionalities in my user study. Tesseract is an interactive exploration environment that visualizes the socio-technical relationships in software projects. It analyzes information from code archives, communication records, and bug repositories to capture the relations between code, developers, software bugs, and communication records. By empirically analyzing data from different project repositories, Tesseract visualizes the file dependencies, communication network, and technical dependencies among developers

based on their underlying work dependencies. Tesseract's built-in features allow developers to explore project resources and socio-technical dependencies across multiple repositories visually and interactively [32].

This work extended Tesseract by providing: (1) enhanced resource finding with synonyms search and similar-bugs search, (2) integration of enhanced bug search features to allow visual exploration and providing more details on bugs, (3) enhanced network visualizations with package-level dependencies, and (4) a set of filters to manage various project resources. With enhanced resource finding and visual exploration, Tesseract now supports a majority of the proposed onboarding functionalities.

To empirically validate the usefulness and effectiveness of these Tesseract functionalities in supporting developer onboarding, I conducted a user study with tasks on: (1) early experimentation and (2) internalizing structures of project resources. This study included twenty participants as novice developers starting on an open source project (GNOME Rhythmbox [29]). In the experiment, subjects were asked to identify the right (starter) task by exploring related issues in the database, expand the focus to identify related resources to the starter task, and answer questions regarding the technical and social structures of the project. My results show enhanced resource finding to be beneficial in enabling early experimentation and visual exploration across project entities to help in building mental models. Subjects when using Tesseract provided more correct answers and in short time to completion. This was confirmed by qualitative feedback from participants, who found Tesseract to help them get an overview of the projects and in identifying related resources.

In summary, my work aims to explore tool support for developers onboarding a software development project. This thesis primarily contributes to three aspects as noted below:

1. It proposes a list of functionalities of tool support for developer onboarding.

2. It extends a project exploration tool with multi-perspective visual exploration and enhanced resource finding to help developers onboard a new project.

3. It evaluates a project exploration tool to understand how these functionalities work in supporting developer onboarding and projected future improvements.

The remainder of the thesis is structured as follows. In Chapter 2, I provide an overview of background and related work on developer onboarding, program comprehension, resource identification, and information retrieval. In Chpater 3, I review recent studies on challenges in developer onboarding and report the results of my pilot study to better understand the onboarding challenges in practice. To address these challenges, I then propose a list of functionalities to support developers onboarding and present my approach to support these functionalities. Section 4 then presents an introduction to Tesseract and explains the implementation details related to extending Tesseract to support developer onboarding. Section 5 evaluates the onboarding support in Tesseract with a formal user study and discusses the results. Section 6 concludes my work with a brief outlook on future work.

Chapter 2

Background and Related Work

In this section, I first provide background on new developer onboarding and program comprehension. I then discuss the technical aspects involved in enabling Tesseract to help in resource finding. Specifically, I explain the information retrieval techniques that can be used to improve search capability over software project resources. Finally, I discuss related work on automated support for resource identification in software development projects.

2.1 Developer onboarding

In management science, onboarding refers to the process where new employees learn the knowledge, skills, and behaviors that they need to succeed in their new organizations [3]. In software development, onboarding (sometimes referred to as a joining script [43]) involves developers to get proficient with a code base and become a member of the development team. Understanding the basic structure of a code base is critical for new developers to get up to speed in a software development project and start contributing. However, software systems may be composed of a large code base

with many lines of code and complex interdependencies, which makes it challenging for new developers to onboard a software project. Relevant research found that novice software developers run into frustration with challenges regarding communication, collaboration, technical difficulties, cognition, etc. [5].

Dagenais et al. [12] performed a grounded theory study of integration of newcomers into a software project and found early experimentation, internalizing structures and cultures, and progress validation to be the three key factors that help newcomers settle in a new project landscape. Each factor impacting developer onboarding is going to be explained in detail in the following paragraph.

Early experimentation refers to developers experimenting with the code base by performing small, often isolated tasks to gain an understanding of the project. In a survey of developers joining new projects, this was considered more valuable and effective than in-depth new developer training or documentation [12]. Newcomers in most projects begin their initial assignments as open-ended code investigations, isolated modifications to the code base, or simple bug fixes [15, 16]. The same characteristics for early experimentation hold true for open source projects; however, here it is the responsibility of the newcomer, instead of the manager, to identify the appropriate technical tasks and start contributing [15, 43]. Most projects have public lists of open issues from which newcomers are encouraged to begin investigating. For example, Rhythmbox [29], a popular Gnome project, has the following recommendation for new developers in its online documentation:"*If you don't know what to work on, or you're looking for a small task to get started, take a look at the list of 'gnome-love' bugs and the current GNOME goals. Otherwise, there are enough bugs and feature requests in Bugzilla to keep anyone busy.*"

The second factor affecting onboarding is the ability to internalize the project structures. This step involves the creation of project mental models, which is a devel-

oper's mental representation of the project and its structures. Building these mental models is closely tied to how developers understand the program and their interdependencies. Research in the area of program comprehension has categorized the cognitive processes and information structures as necessary components for building mental models into different cognition models [44]. I will discuss program comprehension in more detail in Section 2.2.

It is not enough to only understand the technical structure in a project, but it is important to gain an overall understanding of the project: a new developer needs to understand both the technical and social aspects of the project [16]. For example, some of the most common questions asked by developers include both technical and social elements, such as: "who is the person responsible for this component", "what will be the impact of a change", "who has changed this (artifact) in the past", "who can help me with this file". Answering these questions requires an understanding of the team structure and the project history. Unfortunately, the social and technical information pertaining to a project are often treated as dichotomous by existing tools [32].

Note that both early experimentation and creating mental models of the project are integral parts of onboarding and are in fact, symbiotic. Early experimentation tasks help in understanding project structures, which in turn inform early experimentation and vice verse. Both these steps require an understanding of the semantic relationships across different kinds of project entities. Semantic relations are relations that exist implicitly in a project and cannot be directly extracted. For example, two files are likely to be related to each other if they were committed often in the past, which cannot be found directly. Further, it is usually challenging to identify semantic relations since they involve various kinds of project resources. For example, in a communication network, congruence relations (details can be found in Section

4.1), which are mismatches between communication requirements and communication behaviors, are calculated from commits records and communication records across different databases. Unfortunately, most tools do not support the exploration of semantic relationships across project entities. Further, these semantic relationships incorporate project entities that are typically siloed across different repositories [2, 32]. Understanding and managing these semantic relations is difficult enough in a regular software project; they become unmanageable when the scale of the project is in millions lines of code. The current (large) scale of software systems make onboarding tasks cognitively challenging [38].

Finally, the third influencing factor categorized by Dagenais et al. [12] in their study was progress validation. This validation process helps newcomers validate their progress and prevents the situation when they go far off track or get stuck with what they do [12]. Studies have found that newcomers often cannot gauge when a problem is difficult enough and they need help. Frequent progress validation can not only provide an atmosphere where newcomers can feel at ease to ask questions or report their progress, but also present a chance for newcomers to receive proactive suggestions or useful shortcuts straight to the point when they encounter problems. Newcomers can validate their progress either through team feedback where validation can be obtained from team members who know the project landscape well, or by self-checking their task status. Both types were found in [12] to be effective in helping newcomers for a smoother onboarding process.

While all three aspects of onboarding are important, here in this thesis, I discuss early experimentation and internalizing structures which can be aided by automated tool support. In the following sections, I detail how I provide, through my tool, such automated support for new developers during their onboarding process.

2.2 Program comprehension

As I have discussed in Section 2.1, program comprehension is essential to facilitate the onboarding process of developers onto a new project. In program comprehension, developers utilize both existing and newly acquired knowledge to build a mental model of the software project. Depending on their knowledge and project specific contexts developers use different cognition strategies, which are referred to as cognition models [44].

The software engineering cognition models can be largely grouped as *bottom up* and *top down*. The bottom-up model, proposed by Shneiderman and Mayer [33] and Pennington [27], maintains that comprehension is built from the bottom-up by reading source code and then grouping it into higher levels of abstraction (for example, aggregating individual statements into functions, deciphering data or control flow from source). This process of aggregating information continues until a high-level understanding of the program is gained. The top-down model, proposed by Brooks [31] and Soloway and Ehrlich [35], suggests that comprehension occurs in a top-down approach. Brooks' model, for example, states that the comprehension process starts with a hypothesis of the global nature of the program, which is then refined hierarchically. Other researchers have proposed that programmers do not use the models dichotomously, rather they combine strategies of these models based on the context of their exploration. For example, Letovsky's knowledge base model [24] proposes that programmers combine both the top-down and bottom-up approaches "opportunistically". The programmers tend to choose the cognition strategies that they think yield the highest return in knowledge gain in a project. Similarly, Littman et al. [25] and Soloway et al. [36] noted that programmers either use a systematic approach tracing through control-flow and data-flow abstractions or follow an as-needed

approach by focusing only on the code related to a particular task. However, it was found that the "as-needed" approach, although easier to perform, is error prone and inefficient [38]. The programmers explore only the parts of the code base that they believe are relevant to their current tasks. The as-needed approach leads to more errors since casual interactions are often overlooked [36].

Other research in program navigation has shown that a systematic, hypothesis driven exploration is a better alternative [30]. However, new developers face difficulties when using top-down (systematic) comprehension strategies because of their unfamiliarity with the project. Further, such strategies are not well-supported by tools [34]. Instead, new developers are more comfortable, and because of available tool support more successful, when using bottom-up comprehension strategies [26]. Not surprisingly, during early-experimentation tasks new developers were found to employ an as-needed comprehension strategy, investigating code and relevant resources for the current task at hand [12, 16].

In a related study on program comprehension, Sillito et al. [34] analyzed programmer activities into four categories: 1) *Finding focus points* deals with developers finding the "right" starting point to begin their tasks. To achieve this goal developers were found to mainly use text-based search on the code base by identifying keywords or types (classes or interfaces). 2) *Expanding focus points* includes developers attempting to learn more about a given entity and finding information relevant to their task. 3) *Understanding a subgraph* involves developers building concepts in the project pertaining to multiple relationships and entities. To answer these questions, developers have to explore the details and understand the overall structure of the relevant project resources. 4) *Questions over groups of subgraphs* includes developers trying to understand the relationships between multiple substructures in a project

or understand the interaction between a substructure and the rest of the software system.

Note that the first two categories typically involve bottom-up comprehension strategies and map to early experimentation tasks; the next two categories involve top-down strategies and help in creating mental models. Sillito et al. [34] found that new developers largely performed activities in the first three categories. They also evaluated current tool support and found that the third category (overall structure and relationships across structures) was barely supported by current project exploration tools.

To understand the relationships across different project resource structures, developers are required to identify and internalize the complex dependecies between technical structures and social structures, which has been found to be difficult for new developers [5, 16]. New developers were found to spend significant portions of their time in identifying the impact network (which changes in which files can impact which other files and developers [13]). Tools such as Ariadne [41] and OSS browser [15] take the first steps towards visualizing socio-technical relations in a project. Ariadne analyzes the dependencies among code modules to create a network of dependent artifacts, which is then annotated with developers who have edited each code module. OSS browser takes a similar approach, but first creates a network of developers based on their email communications and then annotates developers with the code modules that they have edited. These tools create a hybrid graph of social and technical components by analyzing the versioning repository and the mailing lists (in OSS Browser). Compared to these tools, Tesseract presents three different kinds of networks: file dependencies, communication network, and technical dependencies among developers based on their underlying work dependencies. Further, I include information and developer discussions in the issue tracker in my analysis. I also believe that

presenting the technical and social networks separately makes it easier to comprehend complex networks.

2.3 Resource identification

A key challenge for new developers is the difficulty in identifying the right resources as information about resources are siloed across different repositories and only limited search capabilities are available. Identification of relevant resources of a project is essential for program comprehension. However, the task is nontrivial. For example, a study of the Microsoft's Windows Serviceability group revealed that developers and testers spent significant time during diagnosis looking for similar issues that have been resolved in the past [7]. Developers usually have to manually search for similar issues in a large database. Reading and understanding the comments on each issue can be time consuming too.

Recently, research has attempted to provide tool support for resource identification in software development which we discuss here. Hipikat [42] allows new developers to determine resources that are related to an artifact which they are currently editing. It links different project elements (code, bugs, and discussions in mailing lists) across repositories to recommend related elements. Mylyn [21] is a similar tool that identifies related resources to create a context for a user's task. It monitors a programmer's work activity to identify and recommend information relevant to the current task, which improves productivity of programmers by reducing searching, scrolling, and navigation. One limitation of Mylyn is that it treats tasks independent from each other while in practice tasks tend to be related. This linking of project elements across different repositories is similar to Tesseract. However Hipikat and Mylyn recommend project elements when a user queries about or edits a specific artifact, whereas our

extension to Tesseract [46] allows searching for similar tasks, a key activity in early experimentation

Team Tracks [14] is a tool that provides traces of past navigation (across files) to help with the task at hand. It identifies and visualizes a list of related resources and frequently-accessed items when developers work on a task in a project. Codebook [4] aggregates information about code related changes, developer commits, mail messages etc., to provide information of related resources through a single portal. While these tools link project elements across different repositories and provide a historical view, my work enables tool support for searching for similar tasks: a key activity in early experimentation [12]. Additionally, I provide visual explorations of project structures and their relationships.

Limited search capability is another known problem in current project exploration systems. To search for a relevant resource, in most cases users are required to explicitly mention the fields over which a search is to be performed. Therefore, the quality of the search results is largely dependent on the quality of the query generated by the developer. Furthermore, current search capability is limited by exact keyword matching [1, 12]. For example, issue trackers, such as Bugzilla, Trac, Jira etc., provide search capabilities, but these are limited to exact matching of keywords provided by the developer. Bug patches or code fragments that are often embedded in bug descriptions are not easily identified by search engines, unless they use natural language processing. One exception is InfoZilla [6], a tool that automatically extracts structural information (e.g., code snippets, bug patches, stack traces) from bug reports, which can then facilitate bug triaging and detection of duplicate bugs.

DebugAdvisor [1] is another tool that distinguishes structured text in bug descriptions and provides search functionalities. It uses a two phased approach: the first "search" phase allows users to search using a fat query that contains both structured

and unstructured data describing the contextual information of a specific bug. The second "related-information" phase retrieves resources (people, source files, etc.) from multiple repositories that are related to a set of bug reports (typically limited to a set of five bugs) identified in the first phase by taking into consideration the relationship of the project resources. I do not differentiate structured text from unstructured text in Tesseract and plan on using natural language processing based search in the future.

Recently Natural Language Processing (NLP) is being increasingly used to help in search. For instance, Hill et al. present a context-based search that automatically extracts natural language phrases from source code identifiers and categorizes the phrases and search results into a hierarchy [19]. Latent Semantic Analysis (LSA) is another popular technique that can be used to improve the search capability of search engines. Basically, LSA follows the principle that words that are used in the same contexts tend to have similar meanings. LSA analyzes a large corpus of natural text with statistical computations to extract the contextual-usage meanings of words. With these contextual-usage meanings, LSA uses a mathematical technique called singular value decomposition to identify the similarity of words and text messages [23]. Helping to establish the relations between terms in similar contexts, LSA is able to capture the latent semantic structure in an unstructured collection of text. A search engine using latent semantic indexing can return results that are conceptually similar in meaning to query terms even if the returned documents contains no same keywords as in the query. I plan to use NLP techniques in the future.

My goals, thus far, have been to help newcomers find the right starter tasks and identify relevant resources for these tasks. The user interface of Tesseract is geared to help developers explore related bugs easily and systematically: a developer can drill down into a set of related bugs (and their resources), and other bugs related to the initial set transitively, and retrace their exploration paths. The interactive, visual

presentation of project elements in Tesseract sets my work apart from DebugAdvisor. While DebugAdvisor presents a textual listing of bugs and related resources, Tesseract provides multiple, cross-linked network visualizations; so much so that the use of the Tesseract interface makes it almost trivial to investigate the project state for a selected time period or bug. Finally, while DebugAdvior had a relatively large deployment of the system, it was deployed to developers who were already part of a large team and well versed in the project. Moreover, these developers only provided ad hoc comments. My study, on the other hand, explicitly evaluated onboarding of new developers through a controlled user study.

Finally, resource identification across multiple repositories relies on existing links. However, such links are often missing, especially in open source projects [2]. To overcome the problem of missing links, Linkster [2] allows an (expert) user to manually link project elements through a UI. For example, users can add a link between a commit ID and a bug ID by checking their relationships through the user interface of Linkster. Linkster helps the efficacy of tools and research that depends on such linkages by filling in the missing links. In summary, while current tools allow identification of links based on syntactic information of given program entities, semantic relationships are barely supported [32, 34]. My work attempts to make semantic relationships available to developers, for example, by displaying logical dependency between files and displaying the developers who have edited a set of files.

Chapter 3

Motivation

Here I present my motivation to provide automated support to help new developers onboarding a software engineering project. The first step towards this goal was to locate a set of functionalities that such an automated tool could provide. I performed a literature survey and informal interviews with developers in a pilot study to identify the challenges and the solutions to those challenges. I list the challenges in onboarding followed by a hypothetical example to illustrate the key steps a novice developer will take when onboarding. I then present a list of six key functionalities needed to address the challenges in the onboarding process.

3.1 Challenges in developer onboarding

Recent research has explored the process of onboarding in software development with regard to relevant resource identification, program comprehension, social factors, etc. After reviewing the findings from recent studies on developers onboarding, I identify the following challenges that impede onboarding in early experimentation and internalizing structures.

First of all, it is nontrivial for newcomers to find a good starting point and the resources relevant to the starter task [34]. When developers know little or nothing about the code base, they are interested in finding a place to start looking. A typical starter task for a newcomer could be a small bug fix. However, new developers have difficulty searching for a bug that matches their skill set and interests. Typically they identify an appropriate starter task through a text-based search. However, due to the limited search capability of most issue trackers, it is often challenging to find a good starter task. Further, developers have to identify relevant resources and similar issues to fix a bug efficiently and correctly, but again this is not easy in current software environments. Typically, developers have to manually check the bug lists in the bug database to find the relevant resources needed to complete the starter task. This phase takes significant time and effort.

Second, the investigations of a project currently available to the developers are restricted within the scope of the available "keyword-based" search [12]. In fact, it was found that it is difficult for novice developers to come up with the exact queries to investigate a problem, and the quality of keyword-based search largely depends on the quality of the queries provided by users [22]. For example, when developers search for a bug related to a keyword using keyword-based search, bugs with descriptions containing synonyms of the provided search term do not show in the search results.

Third, it is critical for developers to obtain an overview of the project structures and the interrelationships between different structures. To get familiar with a project, a developer can either find a focus and then expand their focus to relevant resources(formally known as a **bottom-up strategy** [27, 33]), or start from the overall structure of the project and then explore further into the details of an interesting component(formally known as a **top-down strategy** [31, 35]). Both strategies to understand a project require structural views of project resources and their interre-

lationships. However, it is challenging for new developers to obtain such information during the early stage of their onboarding process. Current tools also lack means of presenting and visualizing structural overview of project resources and relationships among those structures [34]. Sim et al. [16] conducted a study of new graduates joining an industry project and found that even after four months of working on a project, developers still had a shallow understanding of the project and got frustrated because of it.

Fourth, project investigations currently have to be performed separately on each individual repository. This makes it difficult for developers to obtain an overview of project dependencies syntactically and semantically [38]. Syntactic relations are relations explicitly specified in program files. For example, two source files can be related because the method defined in a file calls another method defined in another file. Semantic relations are relations that exist implicitly in a project and cannot be directly extracted. For example, two files are likely to be semantically related to each other if they were committed together often in the past. But this relation usually cannot be directly deciphered through static program analysis. Another factor that makes identifying semantic relationships challenging is the fact that they can involve different types of resources. For example, two developers are considered to have communicated with each other if they both commented on the same bug. To investigate a source file, a developer may have to reach out to a static analysis tool to analyze its call dependencies; a configuration management repository to identify its past changes; an issue tracker to keep track of the bugs which are associated with it, and so on. Fragmented explorations between repositories make comprehension of project structures not only difficult, but also time intensive [38].

Further, the majority of tools that support software investigations treat the technical and social aspects of a project as dichotomous. However, technical structure

and social structure depend on each other and studies have shown that understanding the social structure and culture is particularly important in getting assimilated in a project [12, 15]. In a software project, technical structure and social structure depend on each other and developers rely on these dependencies to find someone for help with regard to specific task. Due to the fact that new developers are unfamiliar with the project resources and team structures, they are more likely to ask for help from experienced team members. Thus, it is important for new developers to investigate the technical and social aspects of a project with regard to the dependencies that exist among them.

Finally, the current scale of software systems makes the creation of accurate mental models cognitively challenging [38]. Large software projects tend to consist of millions of lines of code, which may have evolved over decades. Software development teams also can be large and contains hundreds of people. New developer can easily get lost in exploring such a code base with a large history of code commits, bug reports, communication records, documentation, etc. Therefore, it is time consuming and cognitively challenging for novice developers to get a good understanding of an unfamiliar project. In fact, a study by Zhou and Mockus [48] has found that it takes at least three years or so for developers to become fluent in their new project.

3.2 Pilot study for initial feedback

To further understand challenges in developer onboarding and to identify the typical tasks in the onboarding process, I conducted a pilot study with developers performing onboarding tasks and informal interviews with them to get their feedback.

I recruited four subjects for my pilot study: two professionals (P1, P2) with at least four years of work experience and two graduate students (S1, S2) in computer science.

They were given a set of four tasks that simulated onboarding tasks for a GNOME project Rythmbox. The first two tasks required subjects to identify similar issues from the issue tracker (Bugzilla) when provided with keywords about a problem or given a specific bug, after which they were asked to identify relevant resources to fix those bugs (e.g., which files to change, which developers to seek help from). The other two tasks required users to understand the social and technical structures in the project by investigating the Git repository where the source code for Rhythmbox is hosted with the mailing list archives of the project. The tasks in my pilot study are similar to those used in my controlled study and to avoid repetition are described in detail later. As part of the study, I also solicited feedback about the appropriateness of the given tasks for onboarding. All four participants found the tasks to be representative. Subject P1 commented on the tasks in the study:"*When I first start my project in my company, I got a lot to learn. The most difficult part to me was to find someone for help. I had a hard time deciding who to contact. The tasks I just did are pretty close to what I worked on when I was a new developer.*" Another subject (S1) commented "*I would say these tasks are necessary when a developer joins a new project. This happens when you try to understand a project.*"

Subjects completed the first two tasks in about ten minutes, but none could identify all related bugs. For example, subject P1 found only one related bug out of four in Task 1. This was so because he did not try any synonyms of the given keywords. In the second task I saw a similar issue, where P1 did not extract the keywords from the given issue or use synonyms for them. When he was asked why he didn't try alternative keywords, he responded that he didn't like to spend too much time coming up with alternative queries and he often had difficulty in figuring out an alternative query.

While the other subjects performed better than P1, they did not identify all related bugs either. One of the subjects who had 4.5 years of experience as a Quality Assurance manager was the most successful in task completion since she tried multiple synonyms in her search. She commented: "*One of my responsibilities when I worked as QA was to find duplicated bugs. It was always a headache for me to select appropriate keywords related to an issue. If the search engine supports synonyms and similar bugs are just a click away, it definitely saves me a lot of time. I can check the descriptions of similar bugs to locate duplicated ones.*"

The last two tasks in the study required investigation of multiple repositories and could only be partially completed. The professional participants did not have experience in Git and could not complete the majority of these tasks. The rest (S1, S2) had difficulty in understanding the semantic relationships across project entities (social, technical, and socio-technical) since it was not readily available in the repositories and required some pre-processing. For example, a subject (S2) with two years of Git experience commented, "*I can do the tasks in Git but have to spend efforts writing long scripts. Some of the tasks involve querying over other databases like Bugzilla, mailing lists, which would be a headache*".

All subjects found the aggregation, visualization and exploration of entities across repositories to be extremely useful. Subject P1 commented: "*The idea Tesseract visualizes the relationship between bugs and developers is great. It can give me a general idea who I should contact whenever I have questions on a bug. Of course, the features of bug search in Tesseract can also give me more results when I want to find bugs. Selecting key terms is hard.*" Subject S4 commented: "*Don't want to query different repositories separately. (It)would be very helpful to have these information aggregated and visualized*"

3.3 Functionalities to ease developer onboarding

Based on the literature survey and feedback from developers in my pilot study, I propose a list of functional requirements for tool support of onboarding. The left column in Table 3.1 shows tool support requirements to address the challenges that I identified from my literature survey and pilot study.

Table 3.1: Onboarding Requirements and Tesseract Features

#	**Onboarding Requirements**	**Tesseract Features**
1	Identification of relevant resources [1, 12]	Synonym-based search and similar-bugs search
2	Investigation of resources across repositories [2, 32]	Cross-linked displays across different project entities
3	Support investigation of semantic relationships [32, 34]	Semantic relationships (logical dependencies)
4	Exploration of socio, technical, and socio-technical dependencies [32, 16]	Dependencies across files, bugs, developers, and communications
5	Providing high-level overview of project structures [34]	Network-centric views
6	Allowing top-down and bottom-up exploration [38]	Explore issues and related resources; view project structures

Requirement 1 allows identification of relevant resources, which helps novice developers to find a good starting point and the relevant resources needed to complete the starter task. This requirement translates to the improved search capabilities compared to the traditional keyword-based search. Requirement 2 enables investigation of resources across repositories so that developers do not have to investigate each project repository separately. Requirement 3 supports investigation of semantic relationships to help developers capture the implicit semantic relationships between various project resources. With requirement 4, developers are able to explore the socio, techinal, and socio-technical dependencies in an aggregated holistic manner instead of performing

fragmented explorations in each separate structure. Requirement 5 provides a high-level overview of the project structures, which is poorly supported by current project exploration tools [34]. Finally, a tool to support onboarding is required to allow both top-down and bottom-up exploration of a project. When performing early experimentation, developers tend to find a starting point and expand their focus to relevant resources in a bottom-up way. However, when developers try to build mental models of a project, they prefer to start from an overview of the project structure and drill down into components of interest, which involves top-down comprehension. So an onboarding tool should support both top-down and bottom-up exploration so that developers can choose the strategy that suits the context of their exploration.

3.4 Hypothetical scenario of a developer onboarding

To describe how a new developer when starting a new project might require the onboarding functionalities that we have outlined in the foregoing section, we present a hypothetical example.

Let us consider a developer, Ellen, and assume that she wants to start contributing to an open source project. To do so, she first checks the issue tracker of the project and finds several open issues. As she is new to the project she wants to start on a task that only requires small and isolated changes to the code base. Therefore, for each open issue in the system, she investigates similar and related issues that have been recently resolved. While doing so, she finds an issue that is interesting, highly similar to a current issue, and had required changes to only a small subset of non-central files. She then investigates the files that had been modified for this issue and the

developers who were involved in resolving it. To gain an understanding about the scope of the task, she also investigates whether the files involved with the issue had other bugs associated with it, or had been modified in the recent past. Finally, before beginning her task she identifies the developers who had made changes to the files of interest in case she needs help.

In my example, Ellen first locates a set of related resources (issues) to identify the appropriate "starter" task for her *early experimentation* with the code base. To do so, she searches the issue tracker to identify the right task. She then *expands her focus* by investigating related technical and social resources that span multiple repositories. More specifically, Ellen performs a bottom-up exploration of the project space by investigating the open and closed issues and the resources associated with these issues. An alternative (top down) approach could have had Ellen first internalizing the technical structures (file dependencies) in the project to identify non-central files and then checking to see whether there were any open issues involving those files.

The key steps to help Ellen onboard are listed in the left column in Table 3.1. Note that of these, Step 1 largely deals with early experimentation and Step 5 with creation of mental models. The other steps are needed for both activities. Also note that research on cognition models and comprehension has shown that effective comprehension strategies combine both top-down and bottom-up approaches [38], because of which I include it in my list.

Chapter 4

Approaches and Implementation

In this section, I first propose my approaches to support onboarding functionalities by extending Tesseract, a project exploration tool. I then introduce the basic features in Tesseract and describe the extensions I have made to Tesseract to support developer onboarding.

4.1 Approaches to support onboarding

To explore tool support for developer onboarding, I extended a project exploration tool Tesseract to include features to meet the list of requirements for new developer onboarding. The right column in Table 3.1 shows features in Tesseract that support the functionalities required for the onboarding process.

First, different project entities are cross-linked across different repositories and visualized in Tesseract. This allows developers to investigate the project as a whole and identify relations between different types of resources without having to explore different repositories separately. Commit database, bug database and mailing list archives are mined and aggregated to build a file network, developer network and

issue list which are visualized in Tesseract. In addition, these resources are cross-linked so that developers can explore relevant resources to a specific project entity without having to query each database separately. For example, selecting a bug in the issue list, Tesseract highlights the relevant files in the file network and who worked on this bug in the developer network.

Second, Tesseract mines the project data in different repositories and displays semantic relationships for developers. For example, Tesseract visualizes the logical dependency between files in the file network. If two files were committed together with each other very often in the past, they are considered to be logically dependent on each other. As we know in practice, files are often tied to each other in some way if they are created and modified together many times in the source repository. Another example of an implicit relationship caught by Tesseract is that developers are considered to communicate with each other if they commented on the same bug. If two developers commented on the same bug, it is very likely that they checked the comments made by each other. Such semantic relationships are typically hidden and take extra efforts and tools to uncover.

Third, Tesseract computes and displays dependencies across files, bugs, developers and communications. Users can explore these dependencies visually and interactively. For example, selecting a developer will highlight other developers she communicated with, files she committed, and bugs she commented on. With only one click, users get resources relevant to the developers she is interested in, without having to perform individual queries over each repository. In addition, users can explore further into the resources relevant to the selected developer, such as the issues he or she worked on in the past.

Fourth, network-centric views of project resources are provided in Tesseract so that developers can understand project structures from high-level overviews. Tesseract

visualizations include file network, developer network, issues overview, and activity overview. These views are explained in detail in Section 4.1. With these high-level overviews of project structure, new developers can get a holistic understanding of the whole project. For example, the developer network allow users to easily understand the social structure, find the social hubs that most developers communicate with, and how each developers are related to each other.

Fifth, I enhanced resource finding to improve identification of relevant resources in projects, which is the most important extension I have done to Tesseract. With synonym-based search and similar-bugs search, Tesseract allows developers to efficiently find an interesting starter task and the relevant resources for that task. With synonym expansion (indexing a term as well as its synonyms), synonym-based search allows users to search for a keyword as well as its synonyms by querying over a single keyword. Thus users get more results relevant to the keywords in a query. Similar-bugs search recommends a list of bugs similar to a current bug that the developer has selected. The search engine takes the description of the current bug as a query, calculates the similarity between the descriptions of all other bugs and the description of this bug, ranks the bugs by the similarity and returns a number of top-ranked bugs to users. With these additional advanced search features, new developers don't have to spend much time coming up with exact queries or trying alternative queries to search for a relevant resource.

Finally, both top-down and bottom-up exploration of project resources are supported in Tesseract. For example, given a bug to fix for early experimentation, developers can explore issues bottom up by searching for details of a bug and identify relevant bugs to that bug, files and developers. Developers can also understand a project by top-down mental modeling. For example, a new developer may want to get to know more about the key players in the project team since the key players

tend to be familiar with the project and new developers can turn to the key players for help when encountering difficulties. To do this, a developer can check the whole structure of the developer network and find the key player in the developers network. They can then explore the developers this key player communicated with and files committed by this developer. By doing this, a new developer knows who are key players and what part of the project they have expertise on, which will help the new developer to find someone for help later.

4.2 Introduction to Tesseract

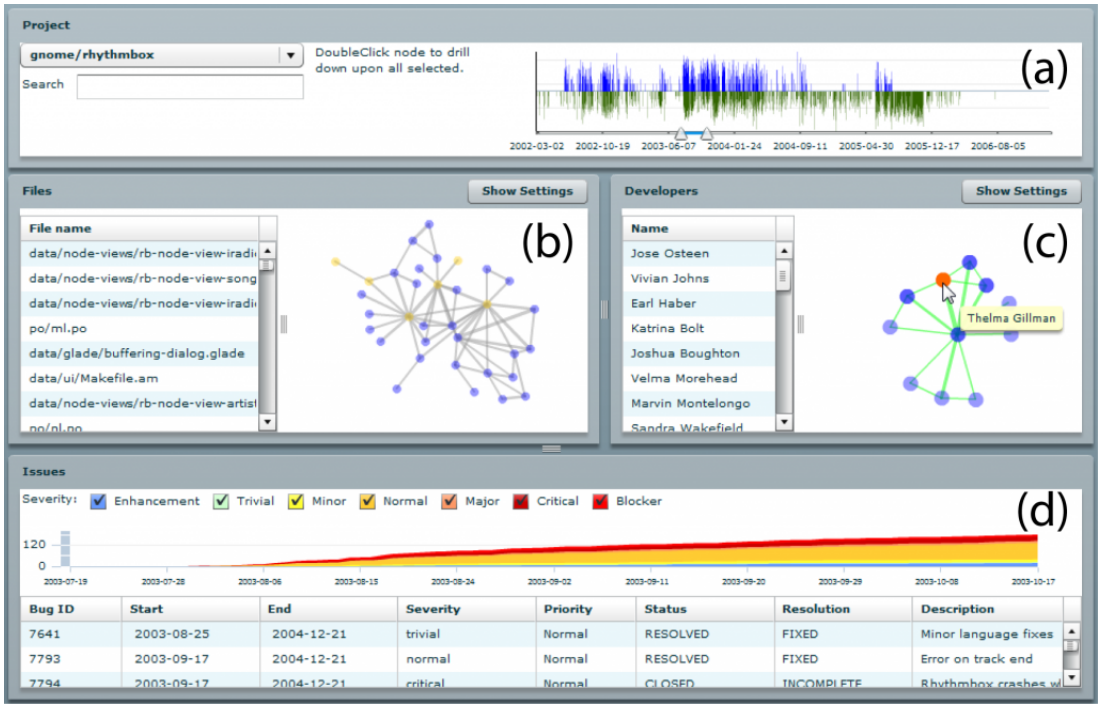


Figure 4.1: Tesseract UI showing four displays: (a) project activity pane with code commits(top) and communication(bottom), (b) file network, (c) developer network, and (d) issues pane

In my study of onboarding I use Tesseract [32], an interactive project exploration tool, as a platform of choice because its built-in features already provide many of the key requirements identified in Section 3. With its interactive, cross-linked displays (see Figure 4.1), Tesseract already supports (see Steps 2 to 6 in Table 3.1): investigation of resources across repositories; investigation of semantic relationships; exploration of socio-technical dependencies; high-level overview of project structures; top-down and bottom-up exploration. Details of this support will be explained after the brief introduction of Tesseract.

Tesseract is a tool for interactive visual exploration of socio-technical dependencies in software engineering projects [32]. It analyzes code archives, communication records, and bug databases to capture the relations between code files, developers, and software bugs. Specifically, Tesseract displays overall project activities(commits and communication), file dependencies(logical coupling between files that have been checked in together), social dependencies(dependencies between developers who have edited the same file or commented on the same bug), bug history, and the interdependencies between files, developers and bugs. It allows users to investigate a project from different perspectives and get a holistic view of the project. Figure 4.1 shows the screenshot of the user interface of Tesseract, which includes four primary displays:

1. The Project activity pane (Figure 4.1(a)) includes a project selection list and a time series display of overall activities in the selected project. Users can select a project from a drop-down list of available projects and then choose a time period from the date slider to explore this project. The date slider is part of the time series display and sets a start date and an end date of the time period that users want to explore. Tesseract populates other panes with file network, developer network, and bug data corresponding to the selected date range. The

distribution data in the times series display provides an overview of project activities, with frequency of code commits on top and communications at the bottom.

2. The Files network pane (Figure 4.1(b)) presents a network of dependent files based on logical dependencies [17], that is, files that have been frequently changed together in the past are considered to be interdependent. Users can set a threshold of the times two files have been committed together in the selected time period for them to be considered interdependent. Files that have been committed together less than the threshold are not considered to be interdependent. The number of times two files are committed together is represented by the thickness of the edges in the network. A textual listing of the file names is provided at the right hand side to allow quick identification of specific files by name. It also allows users to search for a file by name in the file list.

3. The Developers network pane (Figure 4.1(c)) displays the social dependencies among developers based on their communications with each other as recorded in mailing lists or comments and activities in the issue tracker. There are three kinds of edges in the developers network: coordination behavior, coordination requirements, and congruence. The *communication behavior* in the project is based on communication activities in the mailing lists and bug database. Specifically, when developers participate in email discussions, comment on a particular bug/issue in the Bugzilla database, or work on a particular bug/issue they are considered to have communicated with each other. *Coordination requirements* are calculated based on the methodology developed by Cataldo et al [9], where developer to developer dependency is calculated based on the underlying logical coupling among the artifacts (i.e., files that have been committed together).

Congruence is defined as a match between the coordination requirements and the coordination behavior of a team, where developers who are working on interdependent artifacts are meant to coordinate with each other. The coordination behavior link is compared with the coordination requirement link to calculate congruence. When the communication link matches the coordination requirement link, the edge between two nodes in this graph is colored green. When the communication link is missing the edge is colored red representing a gap. When there is an extra communication link (i.e., two developers have communicated, but not worked on coupled artifacts), the edge is colored grey. The developer network panel provides two controls. The thickness of the edges is derived from the number of times developers communicated with each other. This display can also be used to present the impact network among developers because of their underlying work dependencies. That is, if two developers are working on files that are interdependent, changes by one developer might impact the changes made by the other developer. Similar to the file network, it provides a textual listing of the developer names and supports search by developer name.

4. An issues display (Figure 4.1(d)) that lists open issues or feature enhancements in the issue tracker along with a stacked area chart view of the issues. Bug information is shown in the Issues pane if the bug was active in the time range selected by the date slider in the project activity pane. The stacked area chart in the Issues pane displays the number of open bugs in the selected time range. Bugs are classified according to severity and displayed in different colors in the stacked area chart. The bug list under the stacked area chart provides further information on open bugs in the selected time period. Users can check the opened date, the closed date, and the description of a specific bug. *Sever-*

ity indicates the severity of bugs, such as "Blocker", "Critical", "Minor", etc. Severity is a status assigned by the core developers in the project. Each bug has a *Status*, which can be "NEW", "ASSIGNED", "RESOLVED". It shows the status of the bug as reported by the developer working on it. Frequently bugs undergo different stages: open, change in status, close, and resolve. *Resolution* is the final decision about how the bug was resolved. For example, the final status of a bug can be "FIXED", "DUPLICATE", "INVALID".

The four displays are cross-linked and, therefore, allow interactive explorations of underlying relations across project entities. Users can select a bug in the issues pane, which will highlight the developer to whom the bug was assigned, the developers who had communicated regarding that bug, and the files that had been changed as part of the bug fix. Using this information along with the file dependencies graph, users can identify bugs that involve files that are non-central and appropriate for them. Further, clicking on a file highlights the developers who have edited the files in the past and could serve as possible experts from whom they can seek help. In this way, users also interact with the socio-technical relationships among various resources in the project. Tesseract allows users to explore semantic relations by displaying the implicit relations identified from data across different repositories, for example, the logical coupling of files and congruence in communication among team members. The overall activities displayed in the Project pane and network visualization enable users to get a holistic view of the project. The date range selection and drill down features in the visualization enable users to understand the project either top down or bottom up.

Tesseract has been designed as a client-server application with a rich web client. Its architecture is shown in Figure 4.2 [32]. Server side Tesseract is a data extractor.

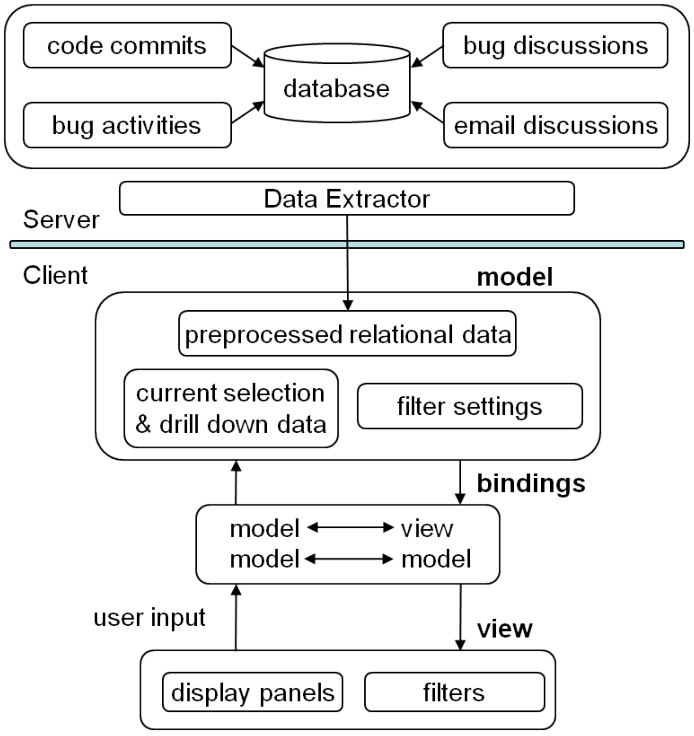


Figure 4.2: Tesseract architecture: a client-server application

It collects and extract project data from code archives, communication records, and bug databases. Client-side Tesseract consists of the data analysis and visualization components, which can be grouped as model, view, and bindings. The *data model* stores preprocessed relational data from server, current selection and drill down data in the application, and filter settings specified by users. *View* includes the various user interface components: bar chart, table, stacked area chart, and graph visualization. *Bindings* exist between model and view components as well as among model components. Data displayed in view components is bound to model data. Data binding among model components exists when model data depends on preprocessed relational data and user configuration data. For example, file network data is recalculated if users change the file commit threshold setting.

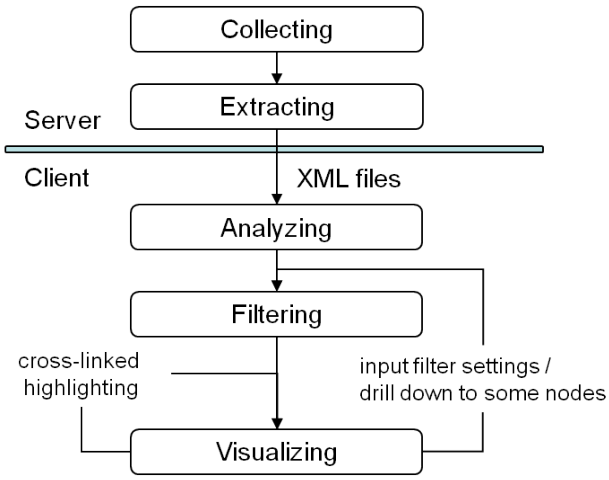


Figure 4.3: Information flow for Tesseract

Figure 4.3 [32] shows the underlying information flow in Tesseract. Data collection and extraction are done at the server side while data analysis and visualization are done at the client side. In the *collecting* phase, Tesseract collects data from a source code management system, one or more project mailing lists, and a common bug or issue tracking database. The collection of data is then extracted and crossed-linked in the *extracting* phase. The cross-linked data is stored in a small set of XML files. On the client side, those XML files are analyzed in the *analyzing* phase to capture (1) relationships among files, developers, and bugs, (2) coordination behavior, coordination requirements and congruence among team members. The *filtering* phase manages information overload by allowing users to set time period, thresholds and communication patterns. The socio-technical relationships are finally visualized in the *visualizing* phase.

4.3 Extensions to Tesseract to support onboarding

While the basic functionalities of Tesseract could help in onboarding, a few requirements in supporting early experimentation and internalizing structures were missing. First, the search capability in Tesseract was very limited. The original implementation of Tesseract only supports keyword-based search over file names and developer names. The search engine returns results that matches the queried terms exactly and it does not allow search over bugs. Second, the original Tesseract has scalability issues. Most projects have hundreds of project artifacts. Visualizing such large numbers of nodes can easily lead to overlap, which makes it hard to understand the network and interact with it. The same issue happens to the developer network when there are many active developers in the software development team. Further, there are multiple types of files in a large project but users may want to explore certain types of files. The original Tesseract does not support such file type filters and cognitive overload still exists with years of data in a project. Third, navigation in Tesseract could be more user friendly. For example, it is difficult for users to find the right time period to explore since there is little time-related information besides the dates spreading over years. Additional release information may help users to know more about the dates they want to explore.

4.3.1 Enhanced resource finding with synonym-based search and similar-bugs search

One of the key requirements in early experimentation is finding the right "starter" tasks (Table 3.1, row 1). For this, I extended Tesseract [46] to include synonyms ex-

pansion of keywords and document-similarity search (Figure 4.1(d)). That is, Tesseract can now identify bugs in the database that are similar, but do not contain the exact phrasing as the keywords in the query. The results of the search are ordered based on their closeness to the original query terms and cross-linked to other resources such as related files, contributing developers, etc., through the Tesseract UI. For example, if users search for bugs that dealt with "playback crashes", the results (see Figure 4.4) would include bugs with descriptions containing the keywords "crash" and "playback", as well as "freeze" and "hang", which are synonyms of "crash". Similarly if users select a bug from the list, the results include synonyms of keywords in the description.

Figure 4.4: Search over bugs in Tesseract with keywords "crash playback"

4.3.2 Information retrieval techniques used

To help developers with resource identification during their onboarding process, I enhanced the search capability by taking advantage of two information retrieval techniques: synonym expansion and document similarity search [46]. Synonym expansion is the process of expanding a word to its variants at either query or indexing time. For example, "crash" can be expanded to "freeze, hang, die" in the context of soft-

ware bugs. I then have to keep a record of the synonyms sets, which is typically done by creating a thesaurus. In my case, I index a word in a document along with its synonyms if the queried word exists in the thesaurus. Details about the thesaurus will be explained in the following section.

Document similarity is a technique that uses different heuristics to retrieve a ranked listing of documents that are similar to a query document [45]. A similarity heuristic is a mechanism that assigns a numeric score indicating how closely a document is related to the queried document [49]. In my implementation, I follow the Cosine Similarity measure based on the vector space model [28] to retrieve similar documents. More specifically, documents and queries are modeled as n-dimensional elements of a vector space (w_1, w_2, w_n), with n being the number of index terms and w_i reflecting the importance of each term i in document or query. As noted in Equation 4.1, term weight w_i is calculated as the product of term frequency (tf_i) and inverse document frequency (idf_i).

$$w_i = tf_i \times idf_i \tag{4.1}$$

idf_i is calculated as in Equation 4.2 with D referring to the total number of documents and df_i being the number of documents with the occurrence of index term i.

$$idf_i = log(\frac{D}{df_i}) \tag{4.2}$$

Using the vector representation of documents and queries, the Cosine similarity between a query and an indexed document is calculated based on Equation 4.3.

$$Sim(q, d) = \frac{\sum_{i=1}^{n} w_{q_i} w_{d_i}}{\sqrt{\sum_{i=1}^{n} w_{q_i}^2 \times \sum_{i=1}^{n} w_{d_i}^2}} \tag{4.3}$$

4.3.3 Implementation of synonym-based search and similar-bugs search

I built the search features in Tesseract using Solr, an open source search platform [37]. The search feature is composed of five phases: analyzing, indexing, searching, querying, and reporting (see Figure 4.5). In the analyzing phase, the search engine retrieves bug data from the Bugzilla database, and analyzes and preprocesses the data through the following steps: (1) stemming, (2) filtering out stop words, and (3) synonym expansion. Stemming is the process for reducing words to their root. For example, "worked", "working" can both be stemmed to "work". Filtering out stop words refers to filtering out words such as "and", "a", "the", that provide little lexical meaning to improve performance. Synonym expansion is explained later in this section. The analysis phase consists of first parsing the descriptive text of a bug into a bag of words (an unordered collection of words). In the indexing phase, the bag of words corresponding to a specific bug is indexed as a distinct document, which is then used in the search phase. Note that synonyms for each term in the bag of words are retrieved from a synonym thesaurus and indexed. In the query phase users can either query by key terms of a software feature or search for a similar bug by selecting a specific bug from the UI. Finally, in the reporting phase, search results are displayed based on a ranking of their closeness to the search query (see Figure 4.4).

An important component of the search feature in Tesseract is the synonym-based search. The first step for synonym-based search was to create a synonyms thesaurus. The bug descriptions of a particular project in Gnome were manually analyzed to determine synonyms, which were then added to the thesaurus. For example:

1. mute, silent

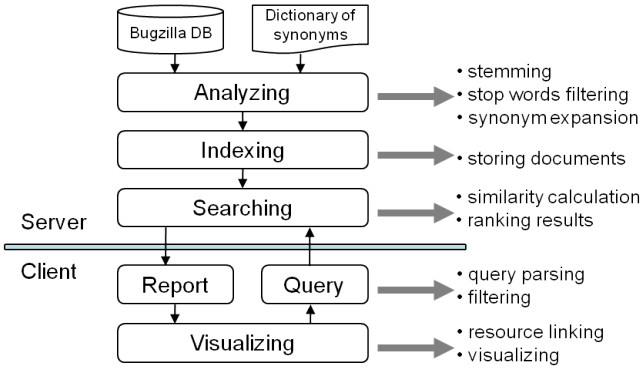


Figure 4.5: Information flow in search engine

2. view, display

3. crash, freeze, die, not working, doesn't work

4. delete, remove

Manually creating the thesaurus was time consuming, but it is a resource that can be reused for other software engineering projects. It took me about twenty hours to analyze 2288 bug records in a project to create 100 synonym entries. Note that there are available resources such as WordNet [47] a large lexical database of English, and ConceptNet [11] a common sense knowledge base that can be used to expand queries by identifying synonyms of search terms. However, these libraries are largely created for the English language and not highly suitable for software engineering contexts.

The next step in the process is synonym expansion, which is performed during the analyzing process. That is, when a term generated from a bug description is being indexed the analyzer first checks whether the term has any synonyms in the thesaurus. If it does then all its synonyms are also indexed as terms. Because of this, when a search is performed all documents that contain the query terms or their synonyms are retrieved. Once a set of query results have been obtained they are ranked based

on the closeness of their (bug) descriptions to the original query. More specifically, I use Cosine similarity (see Equation 4.3) to identify the similarity between the bug description and the query and rank the resultant bug reports accordingly.

The similar-bugs search follows a comparable approach, the main difference being that a user selects a specific bug from the bugs pane list (see Figure 4.1(d)) instead of searching over specific query terms. When a user selects a particular bug, the search engine retrieves the description of the selected bug from the Bugzilla database using the bug ID. It then parses the description and converts it into a bag of words, which are considered the key query terms for the search. The rest of the process is exactly the same as synonym-based search. Once the search engine recommends the "similar" bugs, users can investigate the resultant bugs as well as explore other similar bugs from the result set. The user interface of the similar bugs recommendation report is shown in Figure 4.6.


More bugs like bug 7589: Crash while deleting all songs

Bug ID	Assigned to	Status	Description
8704	RhythmBox Ma	RESOLVED	Crash when deleting a song from context menu.
7992	Jeffrey Yasskin	RESOLVED	crash while deleting currently playing song
8382	RhythmBox Ma	RESOLVED	Crash when deleting playing song
7591	RhythmBox Ma	RESOLVED	I deleted a group of songs (including the current
8148	RhythmBox Ma	CLOSED	Crashed when deleting an internet radio station
9302	RhythmBox Ma	NEEDINFO	crash on trying to play deleted file
9324	RhythmBox Ma	RESOLVED	Iradio crashed when attempting to remove radio

Figure 4.6: Similar bugs recommendation in Tesseract when Bug 7589 has been selected by users

4.3.4 Integration of search features into visual exploration

Implementing the search features required us to make modifications to the original Tesseract architecture. Figure 4.7 shows the additions to the original architecture

through the highlighted modules. Specifically, the search application server and index was added at the backend, new models on bug query and filters were added, and two new UI components were implemented (bug query, bug report).

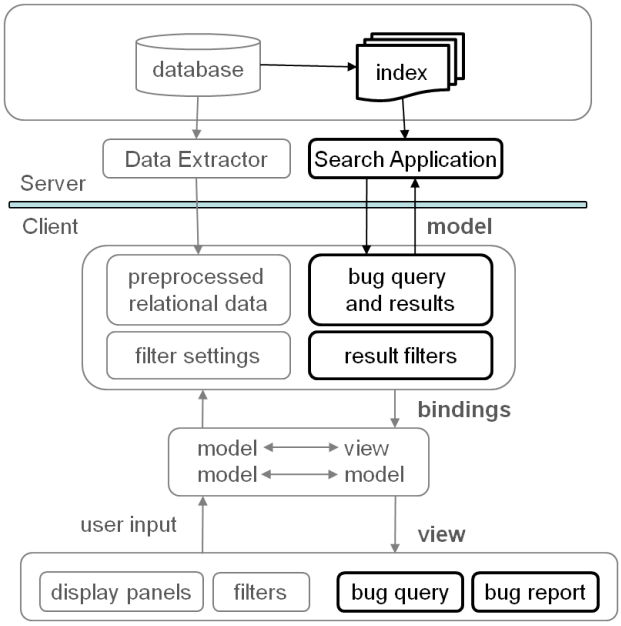


Figure 4.7: Integration of bug search into Tesseract

Additionally, Tesseract now displays more details on bugs (see Figure 4.8). Developers can select a bug and explore details of the bugs, such as all comments from developers, past activities related to bugs, etc.

The interactive project exploration feature provided by Tesseract sets it apart from other existing bug-search tools. Using the search features in Tesseract new developers can visually explore a particular feature, code component, or a bug. They can now easily explore the vast project space to identify other related bugs or feature fixes, the files and developers that were connected to a bug (or related bugs), developers who discussed a bug and have the required expertise, and so on.

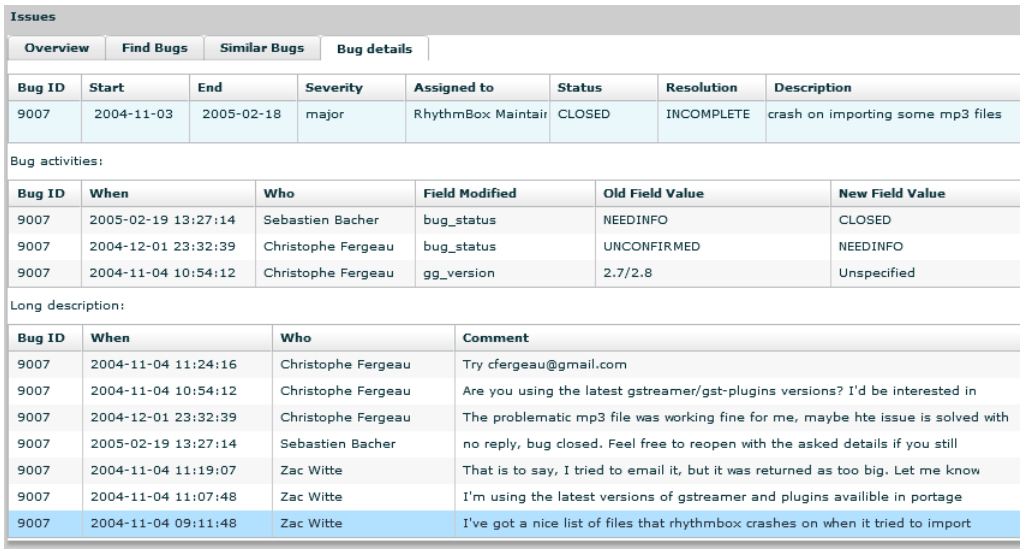
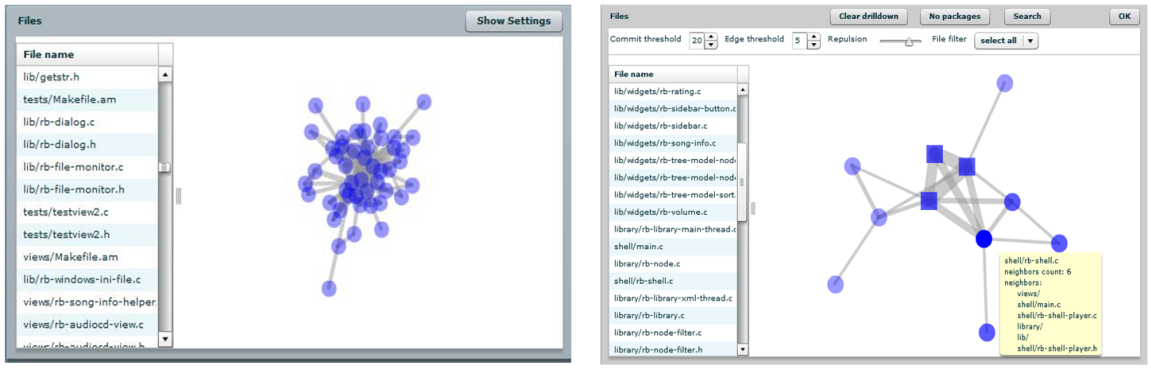


Figure 4.8: Display of bug details in Tesseract

4.3.5 Enhanced visualizations and navigation to solve scalability issue

The original visualization in Tesseract has a couple of limitations. First, the visualization of file network and developer network have scalability issues. When there are hundreds of files in the file network, nodes in the network visualization tend to crowd together or even overlap each other (see Figure 4.9(a)). This makes it hard for users to select a node that they are interested in. Second, too many nodes in a visualization can lead to cognition overload on users. There may be thousands of files in the file network in the entire project. Users may be interested in only a few files in a specific package and not want to explore many other files. Third, there is little information on the nodes in the network visualization. Users may want more information to get to know a file node in the network, such as the physical location of a file in the file system, and the number of files often committed with a file. However, users only know the corresponding file name of a node in the file network. They don't know the

name of the parent directory or package of a file node. Neither do they how many files are related to a specific file. Further, users have to check each edge to get files related to a file node. To resolve these issues, I have extended Tesseract to include more features in network visualization.



(a) (b)

Figure 4.9: (a) Original file network visualization with scalability issues vs. (b) updated file network visualization (2002-06-26 to 2003-02-05)

Figure 4.9(b) displays the file network in the same date range (June 26, 2002 to February 5, 2003). The default display for file-dependencies now lists dependencies across packages, denoted by square-shaped nodes. If two files depends on each other because they were committed often, their corresponding packages are also related to each other. By grouping file nodes in their corresponding package, there are much fewer nodes in the file network. Package level dependency also reduces the cognitive load on developers since it allows developers to explore a specific package instead of displaying all the files in the file network. Drilling down into a package node recursively lists its constituent components (files or sub-packages). Such a view can help new developers to quickly recognize the critical components in the system and get an overview of the system structure.

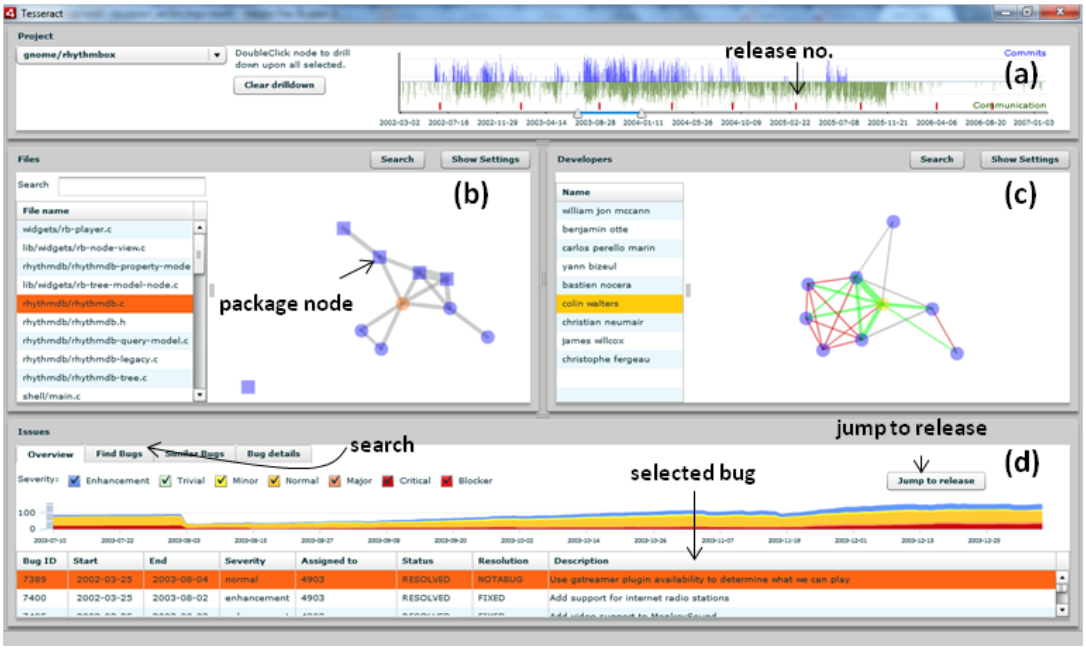


Figure 4.10: Tesseract UI with extensions

Furthermore, Tesseract now provides more relevant information directly to users by adding more information in tooltips. For example, when users investigate the network view of files and developers, the network visualization displays additional information about a node in the tooltip. As shown in Figure 4.10, hovering over a package node lists its constituent files, its neighboring nodes, and a centrality measure (number of relations to other files).

Another difficulty when users explore a project using Tesseract is to find and select the appropriate time period they want to explore. The original implementation of Tesseract only provides a way for users to select a starting date and an ending date of a time period they are interested in. However, new developers are unfamiliar with the project and may not be able to find an exact date of interest. In practice, developers are more likely to explore a specific release, for example, a release that a bug is active in.

To better navigate through various project resources, Tesseract now has its time series display annotated with release dates (see Figure 4.10), which can then be used to investigate a particular period in the project. The release dates are marked on the date selection slider so users know which release a specific date is in when they select a time period to explore. Additionally, users can quickly jump into a corresponding release of a selected bug to explore relevant resources in the project. As shown in Figure 4.10, users can double click a bug entry in bugs list to directly jump to its corresponding release which it was active.

4.3.6 Filters to reduce cognition load

Cognitive overload can be a common problem for new developers when they onboard a large project because of their unfamiliarity with the project landscape [12]. While the network-centric displays of Tesseract alleviates this problem to an extent, I enhanced the Tesseract UI to further facilitate exploration of large projects.

I have implemented a file type filter for the file network display (see Figure 4.9(b)). When performing early experimentation tasks, developers can now choose to only view a specific type among source code files (i.e., filter out files with extensions that are not .c or .h). Such filtering can greatly reduce the visual complexity of the networks.

Since there can be thousands of bugs in a repository, the search engine may return hundreds of bugs for a single query, which increases the cognitive overload on users. I added a date range filter and bug severity filter as advanced features to the search engine in Tesseract. The search engine now allows users to search for bugs over a date range they choose. It also allows users to search for bugs with particular severity types, for example, “Critical” bugs. In addition, users can limit the number of results displayed in the bugs listing.

4.3.7 Summary

In summary, I implemented the following extensions to support developer onboarding in addition to the built-in features of Tesseract.

First, to improve the search capability in Tesseract, I implemented a search engine with synonym-search and similar-bugs search. A bug search query in Tesseract now returns more results with the query terms as well as their synonyms. A similar bugs search feature helps users find more bugs relevant to a specific bug by searching for bugs with a similar description. The search engine is further integrated into the visualization in Tesseract so that users can interactively explore bugs in the search results.

Second, I enhanced the visual exploration in Tesseract with package-level dependencies in the file network and a couple of filters to improve the scalability and reduce the cognitive load for users. In the file network, Tesseract now allows files in the same directory / package to be grouped into a package node, which reduces the density of the nodes in the file network and solves nodes overlapping issues to some extent. Users can drill down into a package node to explore files or sub-packages in it. Tesseract now allows users to select files by types to be displayed in the file network. The advanced features of the search engine provides date range selector and bug severity filter to limit the number of results in a query over bugs.

Chapter 5

User Study

I empirically evaluated the onboarding functionalities as well as the Tesseract features that support developer onboarding through user studies. I ask two broad research questions to evaluate the effectiveness of Tesseract in helping onboarding.

RQ1. How does enhanced resource identification help developers in their early experimentation tasks?

RQ2. How do visual explorations of technical, social, and socio-technical dependencies help developers to gain an understanding of the project's internal structure?

RQ1 investigates how Tesseract helps with early experimentation tasks, while RQ2 deals with creation of mental models. Note that while the advanced search functionality is geared towards early experimentation tasks and the network visualizations towards creating mental models, the remaining features from Section 3.5 are pertinent for both.

In the rest of the section, I first describe my experiment settings and evaluation model. I then present details of the experiment procedure and study results.

5.1 Experiment settings

Based on my pilot studies, I refined the user tasks and the Tesseract UI before performing controlled user experiments, which were conducted at the usability lab at the University of Nebraska-Lincoln and involved twenty participants. In the experiment, participants first filled out a background questionnaire and then were led through a tutorial explaining Tesseract and its features, which was followed by the actual tasks. At the end of the experiment participants filled out an exit survey and were interviewed (semi-structured). Each participant was paid twenty dollars for taking the experiment. Details of the tutorial and tasks are available in Appendix A.

Among the twenty participants, fourteen were male and six female. All were students in the Computer Science and Engineering department at the University of Nebraska-Lincoln. Of the twenty participants fifteen were graduates and the rest advanced undergraduate students. Most students were adept at programming; fourteen of them had more than three years of coding experience. Participants had experience using versioning systems (twelve had used SVN and eight CVS) and issue trackers. All of them had worked in teams and two of them had experience working with a GNOME project. All participants were familiar with searching and used a search engine almost every day.

Table 5.1: Experiment Design

Phase	**Task**	**Task Type**	**Participants**	
			Ctrl	Exp
Early Experimentation	Task 1	Identify related bugs	10	10
	Task 2	Identify related features	10	10
Creating mental models	Task 3	Internalize file structure	20	
	Task 4	Internalize social structure	20	

The experiment was designed in two phases (see Table 5.1). The first phase evaluates the efficacy of Tesseract in helping developers find and expand focus in early experimentation, while the second phase evaluates Tesseract in building mental models of technical and social structures in a project. An alternate, single-phase design could have required participants to resolve a bug by first searching for similar bugs and then understanding the project structures. However, this could have several issues. First, participants could have simply resolved the bug without performing any early-experimentation strategies. Second, the quality of bug resolution would be affected by individual differences caused by differences in experience or skills among participants. Finally, because of time restrictions that govern user studies I could have only assigned simple bugs, which in turn might not have required an in-depth understanding of the project structures for their resolution, thereby, defeating the goal of my study. Therefore, I separately test the early experimentation and mental model tasks in two phases (see Appendix A for more details about user study tasks).

The first phase included two tasks, where subjects were asked to search for past bugs similar to a given issue in the code base of the Rhythmbox project. They were then asked to identify other related project elements (files edited, developer information, etc). This phase involved two treatment groups and a between-subjects experiment design. Participants were randomly assigned to the treatment groups (Control or Experimental). The Control group used basic Tesseract with keyword-only search, while the Experimental group had access to the synonym-based search feature. I do so to evaluate how advanced search functionalities, currently unavailable in issue trackers, can be of help in onboarding. Another alternate design could have required participants in the Control group to use Bugzilla and other repositories. However, based on my pilot study I felt that this would highly bias the experiment in favor of Tesseract. Yet another option could have compared Tesseract with DebugAdvisor [1],

a cross-platform search-based tool. However, DebugAdvisor is a commercial tool and requires significant manual configuration by the user to link project elements. I leave such a comparative evaluation for the future.

The second phase of the experiment was a single treatment study with the main goal to evaluate how visual explorations afforded by Tesseract help in understanding project structures. Tasks in this phase asked participants to use Tesseract to identify central developers, their contributions, social hubs in the project, and so on. My experiment only uses a single treatment variable, since I am not aware of any other project exploration tool that presents all the information provided in Tesseract. Designing an experiment that required users to investigate project structures by analyzing separate repositories would not have been a fair comparison; as corroborated by my observations in the pilot study.

Each experiment phase consisted of two tasks, which were counterbalanced. For example, in the "early experimentation" phase, participants were randomly assigned either Task 1 or Task 2, followed by Task 2 or Task 1, respectively. Participants were asked to playact as new developers who wanted to start to contribute to the Rhythmbox project. The experiment tasks were phrased to create such a context.

The "early experimentation" phase involving Task 1 and Task 2 asked participants to search for related bugs. Task 1 required participants to find all bugs related to a problem with the Rhythmbox application ("the application crashes repeatedly when you remove songs"). Additionally, they were required to identify relevant files for resolving the bug, as well as developers who were involved with a similar bug in the past and could help in its resolution. Task 2 was similar, but this time the context was that the developer wanted to fix a particular bug (bug id: 8077) and needed to identify similar or related bugs. As in the previous case, participants were asked to identify relevant files and developers. As they performed their tasks, subjects noted

the bug ids of bugs that they thought were similar and took screen shots of the networks with the relevant artifacts or developers highlighted.

The "mental model building" phase (Task 3 and Task 4) assessed how Tesseract helped participants in understanding project structures. Task 3 focused on the technical structures, requiring participants to identify the central files in a given release, identify other files that were related to one of the central file ("rb-shell.c"), and identify the developers who had edited that file in the past. Task 4 was similar, but instead focused on the social structure. It required participants to identify the central developers in the communication network, developers who had communicated with one of the central developers ("Colin Walters"), and the files that "Colin" had edited. Subjects noted the names of relevant entities and took screen shots of the networks with relevant entities highlighted as they performed their tasks.

Note that the "mental model building" tasks do not build on the search results of the "early experimentation" tasks. I explicitly split the tasks into the two phases, so that any differences in results of Phase I would not have ripple effects on the outcome of Phase II, especially since Phase I had two treatment groups and Phase II was a single-treatment study.

The entire experiment was logged through screen captures, and exit interviews with participants were audio recorded. Quantitative dependent measures such as, time-to-completion, error rates, correctness and completeness rates were calculated by analyzing the screen captures and answers recorded by users. Qualitative data on user experience was obtained by analyzing screen captures, observation by researchers, and exit interviews.

5.2 Evaluation design

I draw on the usability framework proposed by Hornbaek [20] to evaluate the usability of Tesseract in facilitating onboarding. Hornbaek reviewed current practices in usability measurements by surveying 180 usability studies in the field of Human Computer Interaction (HCI) to present a working model for usability aspects and research challenges associated with measuring each aspect. Hornbaek recommends keeping distinct objective and subjective measures for each aspect and recommends the types of questions and measures to consider when designing a usability study, which I follow.

My evaluation model (see Figure 5.1) tests Tesseract using the three main usability aspects: effectiveness, efficiency, and user satisfaction [14]. Effectiveness measures whether the user can complete tasks, which is evaluated with error rates and number of assists. Efficiency measures the effort it takes to complete the tasks and is often evaluated with time to completion of tasks. User satisfaction measures the participant opinions and attitudes about the product, which can be assessed with satisfaction ratings, questionnaires, and user comments. Note as per Hornbaek, I include objective and subjective measures for both effectiveness and efficiency.

Effectiveness refers to the quality of the outcomes. In my experiment, outcomes are evaluated based on: (1) correctness and completeness rates, (2) error rates, and (3) subjective evaluations of Tesseract. More specifically, I calculated the correctness and completeness rates for "early experimentation" tasks (Tasks 1, 2) and error rates for "mental model building" tasks (Tasks 3, 4). Subjective evaluations of how Tesseract facilitated resource identification and understanding of a project and its interrelationships were collected for tasks (see Table 5.6).

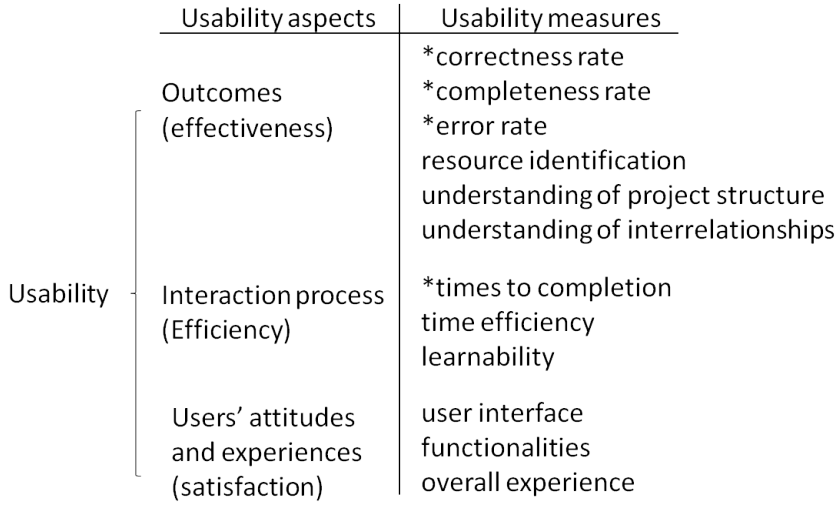


Figure 5.1: Evaluation model used for usability testing. Items with * include objective measures

For all tasks, two researchers individually inspected the data (issue tracker, file and developer dependencies) to create a baseline of correct results. The results from both the researchers were then compared and discussed to create a common baseline. This "results set" was then used to calculate correctness, completeness, and error rates.

Efficiency assesses the extent of effort that users expend when performing tasks. In my case, I measure the efficiency of the interaction process through which users learn to use Tesseract during their tasks. I measure this by reporting the total times per task for each phase and participants' (subjective) perception of time efficiency and learnability when using Tesseract (see Table 5.6).

Satisfaction measures subjects' attitudes and their experiences. Specifically I obtain feedback on the following additional aspects: the overall user interface, Tesseract functionalities, and overall user experience.

5.3 Results and discussion

I present and analyze my experiment results by first discussing the early experimentation tasks, followed by mental model building tasks and my qualitative results.

Early Experimentation: A key step in early experimentation is to identify the right resources, which in my case translates to identifying a robust, initial set of bugs with which to begin investigations (see Table 5.2). For Task 1, I found eight related bugs from manual inspection of bug descriptions. However, the system when using synonym-based search (Experimental group) identified five bugs, which dropped down to three bugs with keyword-only based search (Control group). Similarly, for Task 2, manual analysis of bug descriptions revealed eleven bugs, whereas the system with synonym-based search found ten, which dropped down to seven without it. A key reason for the difference between the number of bugs identified by the search engine and the researchers using manual analysis was the lack of context available to the search engine. For example, in Task 1 subjects had to fix a bug because the application crashed when a song was removed. The keywords extracted from such a definition are: crash, song, and remove. However bug descriptions that used file or playlist instead of song (e.g., "crash on deleting file or playlist") were ignored by the system. Similarly when a bug description used seg fault instead of crash, Tesseract did not detect this. While some of these misses can be corrected by fine-tuning the thesaurus (include seg fault as a synonym for crash), others are context dependent (here file equaled song) and cannot generalize across projects. In the future I will explore including machine learning to self-augment the thesaurus.

Table 5.2 provides the maximum and average bugs discovered by subjects in both treatment groups. Typically, the maximum number of bugs identified by a participant is equal to the maximum number of bugs extracted by the system (Control or

Table 5.2: Summary of number of related bugs found in Task 1 and Task 2 by researchers(Max), the system(System), and subjects(average and maximum) for both treatment groups

		Control			Experimental		
Task	**Max**	**System**	**Avg.**	**Sub max**	**System**	**Avg.**	**Sub max**
T_1	8	3	3.3	4	5	4.5	6
T_2	11	7	6.4	7	10	8.3	10

Experimental group). However, there were two cases in Task 1, one each in Control and Experimental groups, where a subject tried different query phrases and identified an additional bug (row 1, column 5 and 8).

To assess the effectiveness of Tesseract in identifying relevant resources I calculate the completeness and correctness rates for tasks (T_1 and T_2, see Table 5.4), which evaluates the quality of the bug search results. For each bug in the search result, I calculate error rates to evaluate how well subjects identified related files and developers. Table 5.3 lists the terms used for for calculating the completeness and correctness rates.

Table 5.3: Terms used for completeness rate and correctness rate

Term	**Short**	**Description**
True positive	TP	A bug correctly classified as relevant
True negative	TN	A bug correctly classified as irrelevant
False positive	FP	A bug wrongly classified as relevant
False negative	FN	A bug wrongly classified as irrelevant

The correctness rate is calculated as the number of correct classifications divided by the total number of classifications ($TP/(TP + FP)$). The completeness rate is calculated as the number of true positives divided by the total number of true positives and false negatives ($TP/(TP + FN)$).

Table 5.4: Correctness rate and Completeness rate for Task 1, Task 2

	Correctness			**Completeness**		
	Ctrl	**Exp**	**Wilcox p**	**Ctrl**	**Exp**	**MW p**
T_1	0.91(0.15)	0.94(0.14)	0.6909	0.41(0.06)	0.56(0.11)	0.0030*
T_2	0.92(0.18)	0.96(0.07)	0.8521	0.58(0.10)	0.75(0.13)	0.0014*

As we can see from Table 5.4, the Experimental group achieved better completeness and correctness rates. We note that the correctness rates are slightly better for the Experimental group, but the results do not differ significantly between the two groups. Mann-Whitney U tests result in p values that are not significant. A reason for such high (and comparable) correctness rates in both treatment groups is the fact that subjects reported bugs that they considered relevant and humans are inherently good at identifying the relevance of a set of search results since they can easily understand and parse the context of the bug descriptions.

However, I found that identifying an appropriate subset of (relevant) bug descriptions from the entire database is challenging for humans. New developers have been known to face challenges in creating appropriate queries when exploring projects [22]. This difficulty is reflected in the completeness rates of the search results. I found that synonym-based search led to higher completeness rates as it led to identification of more related bugs leading to more true positives. Note that the groups are significantly different from each other for both tasks. Task 1 had a Mann-Whitney $U(MW - U) = 12.5$ with $p < 0.01$ and Task 2 had a $MW - U = 8.5$ with $p < 0.01$. These results show that synonym-based search provides more related bugs, thereby providing a larger set of tasks for users to explore. For each bug in the result set, I found that participants correctly identified the files that had been changed, and the developers who had edited those files or commented on the bug, leading to an error rate of 0.

Next I analyzed the time-to-completion of tasks to investigate whether Tesseract (with synonym-based search) increases efficiency. Table 5.5 lists the time-to-completion for all tasks. In the case of Task 1 and Task 2, I do not find any significant differences between the treatment groups. However, subjects in the Experimental group had identified more bugs (4.5 bugs vs. 3.8 in Task1 and 8.3 bugs vs. 6.4 in Task 2) and investigated the resources associated with those bugs. So, I analyzed the efficiency rate or the time taken per bug across the two groups. I again found the two groups to be comparable. For Task 1, the Control group took 94.7 seconds per bug, while the Experimental group took 65.49 seconds per bug. The two groups only differ marginally (MW-U = 27.5 and p=0.096). In Task 2, the treatment groups were even closer (Control: 48.83 sec, Experimental: 48.23 sec) with no significant differences.

Table 5.5: Time-to-completion(in minutes) for Task 1 through Task 4

Tasks	**Completion times(minimum)**		**MW p-value**
	Ctrl	**Exp**	
T_1	4.91(2.195)	4.65(1.175)	1.000
T_2	5.21(2.029)	6.67(2.047)	0.1051
T_3	5.49(1.791)		n/a
T_4	5.75(1.146)		n/a

Despite the closeness in the efficiency rates, I found that subjects in the Control group made more attempts in formulating search queries. However, due to the limited complexity of my tasks, extra queries were easy to formulate and did not temporally disadvantage subjects. For example, Participant P2 when formulating the search query for Task 1, first used the query “crash”, which resulted in too many results, she then modified the query to “crash + song”, which still resulted in a very large set. She then used “crash + remove + song” which resulted in a null set. She then changed the query to use delete instead of remove, which produced the resultant set

that she finally investigated. So, while this subject had to modify her query four times, she did it in rapid succession as she was well versed in searching.

Mental model building: This phase included tasks that assessed how interactive visual explorations provided by Tesseract enabled users to understand the technical and social project structures and dependencies.

The primary goal in Task 3 was to understand the technical structure in the project and constituted three steps, requiring users to first understand the general dependency structures in the project followed by "drilling down" on the socio-technical dependencies surrounding an artifact. More specifically, subjects had to first identify the central artifacts in the file-dependency network as determined by the number of edges (degree centrality) connecting the node. One of the central files was "rb-shell.c", followed by two other nodes. These files had around fifteen neighbors each. Subjects were then asked to drill down on "rb-shell.c" to identify which other files were dependent on it and might be affected by changes; there were fourteen such dependent files. Third, they had to identify developers who had edited that file in the past and may therefore be of help; there were eight past developers.

I calculated error rates for each step in the task, which was calculated by matching the answers provided by participants with my baseline of correct answers. Subjects were considered to have an error if the answers provided by them did not exactly match my baseline (answers with false positives were considered erroneous). Error rates per step, per task were calculated as the total number of erroneous answers divided by the total number of answers. I found that all participants correctly identified the central artifacts (error rate = 0). However, there was one erroneous answer for "file-dependencies" (error rate = 0.07) and two erroneous answers for "past-developers" (error rate = 0.14).

Further analysis of the experiment videos revealed two participants who gave erroneous answers. One participant (P4) investigated the wrong time period, therefore, analyzing the wrong networks. Because of this, he only correctly identified one dependent file and six developers. The other participant (P8) misunderstood the task, and instead of identifying developers who had edited "rb-shell.c" calculated all the developers in the communication network; identifying twelve instead of eight developers. Note, that some of the above effects are due to my experimental settings (i.e., in real projects developers are unlikely to misunderstand their task). However, novice developers could mistakenly investigate wrong time periods. To alleviate this situation, Tesseract now provides a "jump to release" button from the search page and visual cues about the release that is under investigation (see Figure 4.10).

Task 4 assessed the effectiveness of Tesseract in facilitating the understanding of social structures in a project and included four steps. Participants were asked to find the social hubs in the communication network; "Colin Walters" was found to be the most central node (seven edges), followed by two developers with five edges each. In the next two steps, subjects had to identify which other files that "Colin" had committed (twenty-one files) and other developers with whom he communicated (two developers). The final step asked subjects to identify the (other) primary contributors based on the number of files that they committed; there were three other primary contributors. I found that all participants correctly identified all answers (social hubs, developer contributions, communication edges, and primary contributors) leading to an error rate of "0" for all four steps in the task. Next I analyzed the time-to-completion of these tasks (see Table 5.5). I found that the average time to completion for Task 3 was 5.49 minutes, followed by 5.75 minutes for Task 4. While I did not compare Tesseract with other traditional versioning tools and issue trackers, note that the literature suggests that internalizing the project structures and dependencies is

usually challenging to newcomers and requires significant effort and time on their part [13, 15].

User satisfaction: I collected user satisfaction ratings through exit surveys (5-point Likert scale) and semi-structured interviews. Table 5.6 summarizes the survey results (see Appendix B for more details). All participants had very favorable reviews across all categories with both Control and Experimental groups reporting high satisfaction ratings. Participants were highly satisfied with synonym-based search and similar-bugs search. In Task 1 and Task 2, subjects in the experimental group used the advanced search features in Tesseract and rated their experience based on a 5-point Likert scale, where 5 is "strongly satisfied". The search engine enhanced by synonym-based search is rated at an average of 4.71 and similar-bugs search is rated at an average of 4.57. For example, Participant P4 commented: "*Similar bug search is good. Not only can it search bugs on keywords you input, it also finds bugs with similar descriptions.*" Another reports: "*It's pretty cool, if I input "remove" it also lists synonyms.*"

Table 5.6: User Satisfaction ratings based on a 5-point Likert scale, where 5 is "strongly satisfied"

Categories	**Average(SD)**	
	Ctrl	**Exp**
User interface	4.14(1.069)	4.14(0.690)
Understanding of the project	3.86(0.690)	4.29(0.756)
Resource identification	4.29(0.756)	4.29(0.756)
Network visualizations	4.29(1.113)	4.00(1.000)
Search capability	4.43(0.787)	4.71(0.488)
Similar bugs recommendations	n/a	4.57(0.535)
Learnability	4.86(0.378)	4.57(0.535)
Time efficiency	4.00(1.000)	4.29(0.535)
Overall experience	4.43(0.787)	4.43(0.787)

While synonym-based search was found to be advantageous, participants were much more impressed by the Tesseract user interface, its novelty, and how easy it made investigations of project dependencies. Participant [P1] notes how Tesseract made early experimentation particularly easy for him: "*(Tesseract) definitely saved my time. Definitely. Right now I understand some of the underpinnings of Rhythmbox like how everything is working. If someone gives a Rhythmbox whole folder or zip folder and say try to fix a bug in this, I would have no idea.*"

Participant P15's quote sums up the user sentiments: "*With Tesseract, I can definitely save time in exploring a new project. It helps me identify the file structure as well as the developer organization. I can easily find the primary contributors, central artifacts, and get an idea of the whole software structure. Whenever I want to find some people to get help, Tesseract can give me a hint.*"

Finally, it was found that participants could easily learn to use the system interface (4.86 and 4.57 scores for learnability by Control and Experimental groups, respectively, see Table 5.6). Participant P13 notes that he would recommend Tesseract to others since: "*It is very easy for beginners to learn how version system and bug maintenance work rather than jumping into something like (command line version system) which is very difficult to understand where there's no visual interface.*"

I also collected the possible improvements to Tesseract as suggested by user feedback. First, file listing with a hierachy structure will help users easily find a file they are interested in and get an overview of the physical file structure. Current file listing in Tesseract is a plain list of file names in alphabetical order and does not give any information the hierarchy structure of the file system. Second, Tesseract may allow users to go back to a higher level of package when they drill down to explore further in the file hierachy. Currently users have difficulty going back to the previous level of package they have just explored in the file network. A search history over bugs

may also be stored so that users can check the results of previous searches when they search for similar bugs. One of the possible UI improvements suggested by users is relocation of search boxes. Currently, there two separated search boxes for files and developers. Multiple search boxes make users confused when they try to find a search box in which to input a query. Additional text information about current selected project and time period can be listed besides the date selection slider to help users easily know the context of their exploration. Highlighting of relevant resources can also be better. When a user clicked on a file, all relevant files, developers and bugs are highlighted. These relevant resources are also highlighted when a user clicked on a developer. The only difference is the color of the clicked resource entity. However, users may not be able to notice the slight difference and get confused at which entity is clicked. Some users even suggest a dashboard report for managers to monitor onboarding activities of new developers, for example, what tasks a new developer is working on, which team members a new developer has communicated with, and if a new developer gets stuck on some tasks. This kind of report can help managers to validate the onboarding process of new developers.

5.4 Threats to validity

In experiment design, external validity refers to the generalizabilty of the results of a research study. Internal validity refers to the validity of the (causal) inferences in a research study. Construct validity refers to the extent to which the experiment setting actually reflects the construct under study. Here I discuss the threats to validity in my study. I discuss the threats to external validity and internal validity, followed by the threats to construct validity.

Threats to external validity: One threat is that students were used as participants instead of developers. However, since my study was meant to study onboarding of new developers and all students were advanced students with several years of programming experience, I feel that my results are generalizable to industry settings where new postgraduates join projects. Another threat is that my tasks might not be representative of tasks that developers face in real life. However, I minimized this issue by using bugs and project data from an actual open source project. Finally, my experiment only involved one GNOME project; other software projects might display different characteristics.

Threats to internal validity: One threat can be the small sample size of subjects, which is limited to ten in each group in the early experimentation tasks. To estimate the sample sizes, I calculate Cohen's d value, which is often used in measuring effect size of statistical analysis. I chose to calculate the effect sizes for the early experimentation tasks since these involved two treatment groups. Even though I have a relatively small sample size, Cohen's d for completeness rates in T_1 is 1.73 and T_2 is 1.48. Note Cohen's d values > 0.8 are considered "large" effects, which indicates no necessity of larger sample sizes. Further, to avoid any statistical conclusion issues, I also use non-parametric testing (MannWhitney U Test) which is considered robust for small sample sizes. Another threat comes from researcher bias in designing the tasks for the user study. All four tasks in the experiment are created by researchers instead of being randomly chosen from real tasks in practice. To reduce these biases, I took the following steps: (1) I investigated common onboarding tasks used in practice through literature survey. (2) I interviewed industry partners to get an idea of the type of onboarding tasks, and (3) I interviewed participants in the pilot study about the appropriateness of the tasks for onboarding. Finally, there is a threat of learning effects on results across the four tasks. I minimized this threat by counterbalancing

tasks in each phase. I note that it is likely that subjects in the second phase (mental model building) will demonstrate learning effects from the previous phase, however, since this phase was a single-treatment study learning effects equally affect all participants. In fact, I observe that learning effects also will take place in real life and is in fact desirable.

Threats to construct validity: The choice of our tasks in the user study to measure benefits for onboarding can construe a threat to construct validity. These tasks are only a subset of all possible onboarding tasks in real-world software development and may not be representative of all onboarding tasks that a new user will face. However, these tasks were created based on findings by previous studies on onboarding. Further, our subjects in the pilot found the tasks to be representative of tasks in industry. Finally, while our four tasks were specifically created to investigate how users could identify relevant resources and project structures, it is possible that our task structures and the data represented in Tesseract might not be accurate measures of how newcomers would identify resources or understand project structures. Only an in depth field study investigating how newcomers use Tesseract can accurately answer this question.

Chapter 6

Conclusion

Onboarding a project is challenging for both new developers as well as experienced developers. The challenges during onboarding include: difficulty in identifying the right starting points; limited search capabilities that are restricted to individual repositories; inability to form accurate mental models of project structures and their semantic relationships; and cognitive overload.

In this thesis, I propose a set of onboarding requirements and how those requirements can be met through automated support. Based on a literature survey of developer onboarding and its challenges, informal interviews with some industry partners, and pilot studies, I identify a list of functional requirements to support developer onboarding: (1) identification of relevant resources to aid early experimentation, (2) seamless investigation of data that is fragmented across multiple repositories, (3) investigation of semantic relationships, (4) exploration of social, technical, and socio-technical dependencies, (5) representation of high-level project structures, and (6) facilitating top-down and bottom-up comprehension strategies.

Further, I extended Tesseract to achieve these onboarding functionalities. Tesseract's built-in features already support most of the functionalities required by devel-

oper onboarding. It allows developers to explore project resources and socio-technical dependencies across multiple repositories visually and interactively [32]. This work extended Tesseract with (1) enhanced resource finding with synonym-based search and similar-bugs search, (2) integration of enhanced bug search features into visual exploration and providing more details of bugs, (3) enhanced network visualizations with package-level dependencies, and (4) a set of filters on various project resources. With enhanced resource finding and visual exploration, Tesseract now supports a majority of the onboarding functionalities I proposed.

I performed user studies to evaluate these onboarding functionalities in Tesseract. I found that synonym-based search, previously used in software maintenance tasks [19], also helps in onboarding. More specifically, synonym-based search allowed higher completeness rates among participants in my study. I also observed that participants in the Control group, despite being adept in searching and experienced in programming, did not typically use synonyms in their queries. This is inline with past studies that have shown new developers to have difficulty in investigating a code base [22]. Therefore, I posit that synonym-based search will help in early experimentation. A caveat to my result is that synonym-based search over complex or long bug descriptions could result in large sets of "starter" tasks that would need fine-tuning. While synonym-based search was successful, the most notable benefit of Tesseract was in helping users build accurate mental models of project structures quickly through its cross-linked, network-centric visualizations. Subjects were able to complete tasks with low error rates and in short time-to-completion. Past studies have observed that creating accurate mental models is one of the most challenging tasks for newcomers [5] and that they are frequently frustrated by their shallow understanding of projects [16]. My results and participant feedback show that interactive, project ex-

ploration functionalities that visualize socio-technical dependencies of project entities can help in creating accurate mental models and in short time-to-completion.

Appendix A

User Study Tasks

A.1 Task 1

You were just introduced to the Rhythmbox Gnome project. Now you are looking for a small task to get started. You played with Rythmbox by running the application for a while. Unfortunately, it crashed when you removed a song from the playlist. So you want to start your contribution by fixing this bug. To understand this bug, you want to find all previous bugs related to crashes caused by removing songs. You also want to find which files to work on, who to seek help from and whether you can learn from previous bugs related to crashes caused by removing songs. Specifically, you will take following steps:

1. Find all the bugs about crashes caused by removing songs. You have to check bugs description to decide if they are really related to the same problem.

2. For each bug, check the details of this bug, write down its status. Then find the developer to seek help from(the developer that the bug was assigned to).

3. For each bug, find developers who commented on this bug. Some bugs may have no developers that commented on it.

A.2 Task 2

You were just introduced to the Rhythmbox Gnome project. Now you are looking for a small task to get started. You took a look at the list of bugs in Bugzilla and checked their descriptions. You have found bug 8077 interesting and want to start from it. To get to know this bug, you want to find which files to work on, who to seek help from and whether you can learn from other bugs which might be related to this one. Specifically, you will take following steps:

1. Find all the bugs related to bug 8077. You have to check bugs description to decide if they are really related to the same problem.

2. For each bug, check the details of this bug, write down its status. Then find the developer to seek help from(the developer that the bug was assigned to).

3. For each bug, find developers who commented on this bug. Some bugs may have no developers that commented on it.

A.3 Task 3

You were just introduced to the Rhythmbox Gnome project. Now you want to know more about source files in this project and the relationships between them.

In Tesseract, you checked the Files network of release 2.2 and found file “rb-shell.c” under “shell” folder was a core file (a file that was often committed together with other files). So you want to start from it.

You are going to check who contributed to this file and what other files it was often committed with. You also want to further understand the file structure of this project. Specifically, you will take following steps:

1. Select time between release 2.0 (2002-06-26) and release 2.2(2003-02-05).
2. Find file "rb-shell.c" under "shell" directory.
3. List files often committed together with this file. Count the total number and paste the screenshot of the files network graph with "rb-shell.c" highlighted into the MS Word document.
4. List the developers that committed this file. Count the total number and paste the screenshot of the developers network graph with corresponding developers highlighted into the MS Word document.
5. Find the central artifacts in this time period (note: a central artifacts is a file that was often committed with other files in the current file network).

A.4 Task 4

You were just introduced to the Rhythmbox Gnome project. Now you want to know more about people working on this project and the social relationships between them.

In Tesseract, you checked the Developers network of the current release and found Colin Walters was a core developer (a developer that communicates with most other developers). So you want to start from him.

You are going to check what contributions he did in previous releases and how he communicated with other developers. You also want to further understand the social structure of this team. Specifically, you will take following steps:

1. Select time between release 2.0 (2002-06-26) and release 2.2(2003-02-05).

2. Find developer “colin walters”.

3. List the developers he communicated with. Count the total number and paste the screenshot of developers network graph with colin walters highlighted into the MS Word document.

4. List the files committed by him. Count the total number and paste the screenshot of the files network graph with committed files highlighted into the MS Word document.

5. Find the primary contributor(s) in this time period(note: main contributor is the developer who did the most commits).

6. Find the top 2 social hubs in the developers graph (note: a social hub is a developer that communicated with many other developers).

Appendix B

User Satisfaction Ratings in Exit Survey

B.1 User satisfaction ratings in control group

Table B.1: User Satisfaction ratings in control group based on a 5-point Likert scale, where 5 is "strongly satisfied"

Subject	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**
User interface	5	4	2	5	5	4	4
Understanding of the project	4	4	3	3	4	5	4
Resource identification	4	5	3	4	5	5	4
Network visualizations	4	4	2	5	5	5	5
Search capability	5	4	3	5	5	4	5
Learnability	5	5	4	5	5	5	5
Time efficiency	5	4	2	4	4	4	5
Overall experience	5	4	3	5	5	5	4

B.2 User satisfaction ratings in experimental group

Table B.2: User Satisfaction ratings in experimental group based on a 5-point Likert scale, where 5 is "strongly satisfied"

Subject	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**
User interface	5	4	4	4	5	4	3
Understanding of the project	5	4	4	5	5	4	3
Resource identification	4	5	4	4	5	5	3
Network visualizations	4	3	3	5	5	5	3
Search capability	5	4	5	5	5	5	4
Similar bugs recommendations	5	4	5	4	5	5	4
Learnability	4	4	5	5	5	5	4
Time efficiency	5	4	5	3	5	5	3
Overall experience	5	4	4	5	5	5	3

Bibliography

[1] B. Ashok, Joseph Joy, Hongkang Liang, Sriram K. Rajamani, Gopal Srinivasa, and Vipindeep Vangala. Debugadvisor: a recommender system for debugging. In *Proceedings of the the 7th joint meeting of the European software engineering conference and the ACM SIGSOFT symposium on The foundations of software engineering*, ESEC/FSE '09, pages 373–382, New York, NY, USA, 2009. ACM.

[2] Adrian Bachmann, Christian Bird, Foyzur Rahman, Premkumar Devanbu, and Abraham Bernstein. The missing links: bugs and bug-fix commits. In *Proceedings of the eighteenth ACM SIGSOFT international symposium on Foundations of software engineering*, FSE '10, pages 97–106, New York, NY, USA, 2010. ACM.

[3] Talya N. Bauer and Berrin Erdogan. *Organizational socialization: The effective onboarding of new employees*, pages 51–64. APA Handbooks in Psychology. American Psychological Association, 2010.

[4] Andrew Begel, Yit Phang Khoo, and Thomas Zimmermann. Codebook: discovering and exploiting relationships in software repositories. In *Proceedings of the 32nd ACM/IEEE International Conference on Software Engineering - Volume 1*, ICSE '10, pages 125–134, New York, NY, USA, 2010. ACM.

[5] Andrew Begel and Beth Simon. Struggles of new college graduates in their first software development job. *SIGCSE Bull.*, 40:226–230, March 2008.

[6] Nicolas Bettenburg, Rahul Premraj, Thomas Zimmermann, and Sunghun Kim. Extracting structural information from bug reports. In *Proceedings of the 2008 international working conference on Mining software repositories*, MSR '08, pages 27–30, New York, NY, USA, 2008. ACM.

[7] Shilpa Bugde, Nachiappan Nagappan, Sriram Rajamani, and G. Ramalingam. Global software servicing: Observational experiences at microsoft. In *Proceedings of the 2008 IEEE International Conference on Global Software Engineering*, pages 182–191, Washington, DC, USA, 2008. IEEE Computer Society.

[8] Bugzilla - bug tracking used by the Mozilla projects. http://www.bugzilla.org/.

[9] Marcelo Cataldo, Patrick A. Wagstrom, James D. Herbsleb, and Kathleen M. Carley. Identification of coordination requirements: implications for the design of collaboration and awareness tools. In *Proceedings of the 2006 20th anniversary conference on Computer supported cooperative work*, CSCW '06, pages 353–362, New York, NY, USA, 2006. ACM.

[10] Mauro Cherubini, Gina Venolia, Rob DeLine, and Andrew J. Ko. Let's go to the whiteboard: how and why software developers use drawings. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, CHI '07, pages 557–566, New York, NY, USA, 2007. ACM.

[11] ConceptNet - a practical commonsense reasoning tool-kit. http://csc.media.mit.edu/conceptnet.

[12] Barthélémy Dagenais, Harold Ossher, Rachel K. E. Bellamy, Martin P. Robillard, and Jacqueline P. de Vries. Moving into a new software project landscape. In *Proceedings of the 32nd ACM/IEEE International Conference on Software*

Engineering - Volume 1, ICSE '10, pages 275–284, New York, NY, USA, 2010. ACM.

[13] Cleidson R. B. de Souza and David F. Redmiles. An empirical study of software developers' management of dependencies and changes. In *Proceedings of the 30th international conference on Software engineering*, ICSE '08, pages 241–250, New York, NY, USA, 2008. ACM.

[14] Robert DeLine, Mary Czerwinski, and George Robertson. Easing program comprehension by sharing navigation data. In *Proceedings of the 2005 IEEE Symposium on Visual Languages and Human-Centric Computing*, pages 241–248, Washington, DC, USA, 2005. IEEE Computer Society.

[15] Nicolas Ducheneaut. Socialization in an open source software community: A socio-technical analysis. *Comput. Supported Coop. Work*, 14:323–368, August 2005.

[16] Susan Elliott Sim and Richard C. Holt. The ramp-up problem in software projects: a case study of how software immigrants naturalize. In *Proceedings of the 20th international conference on Software engineering*, ICSE '98, pages 361–370, Washington, DC, USA, 1998. IEEE Computer Society.

[17] Harald Gall, Karin Hajek, and Mehdi Jazayeri. Detection of logical coupling based on product release history. In *Proceedings of the International Conference on Software Maintenance*, ICSM '98, pages 190–, Washington, DC, USA, 1998. IEEE Computer Society.

[18] Git - Fast Version Control System. http://git-scm.com/.

[19] Emily Hill, Lori Pollock, and K. Vijay-Shanker. Automatically capturing source code context of nl-queries for software maintenance and reuse. In *Proceedings of the 31st International Conference on Software Engineering*, ICSE '09, pages 232–242, Washington, DC, USA, 2009. IEEE Computer Society.

[20] Kasper Hornbaek. Current practice in measuring usability: Challenges to usability studies and research. *Int. J. Hum.-Comput. Stud.*, 64:79–102, February 2006.

[21] Mik Kersten and Gail C. Murphy. Using task context to improve programmer productivity. In *Proceedings of the 14th ACM SIGSOFT international symposium on Foundations of software engineering*, SIGSOFT '06/FSE-14, pages 1–11, New York, NY, USA, 2006. ACM.

[22] Todd Kulesza, Weng-Keen Wong, Simone Stumpf, Stephen Perona, Rachel White, Margaret M. Burnett, Ian Oberst, and Andrew J. Ko. Fixing the program my computer learned: barriers for end users, challenges for the machine. In *Proceedings of the 14th international conference on Intelligent user interfaces*, IUI '09, pages 187–196, New York, NY, USA, 2009. ACM.

[23] Thomas K Landauer and Susan T. Dutnais. A solution to platos problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological review*, pages 211–240, 1997.

[24] Stanley Letovsky. Cognitive processes in program comprehension. In *Papers presented at the first workshop on empirical studies of programmers on Empirical studies of programmers*, pages 58–79, Norwood, NJ, USA, 1986. Ablex Publishing Corp.

[25] David C. Littman, Jeannine Pinto, Stanley Letovsky, and Elliot Soloway. Mental models and software maintenance. *J. Syst. Softw.*, 7:341–355, December 1987.

[26] Nancy Pennington. Comprehension strategies in programming. In Gary M. Olson, Sylvia Sheppard, and Elliot Soloway, editors, *Empirical studies of programmers: second workshop*, pages 100–113. Ablex Publishing Corp., Norwood, NJ, USA, 1987.

[27] Nancy Pennington. Stimulus structures and mental representations in expert comprehension of computer programs. *Cognitive Psychology*, 19:295–341, 1987.

[28] Vijay V. Raghavan and S. K. M. Wong. A critical analysis of vector space model for information retrieval. *Journal of the American Society for Information Science*, 37(5):279–287, 1986.

[29] Rhythmbox - music management application for Gnome. http://projects.gnome.org/rhythmbox/.

[30] Martin P. Robillard, Wesley Coelho, and Gail C. Murphy. How effective developers investigate source code: An exploratory study. *IEEE Trans. Softw. Eng.*, 30:889–903, December 2004.

[31] Ruven and Brooks. Towards a theory of the comprehension of computer programs. *International Journal of Man-Machine Studies*, 18(6):543 – 554, 1983.

[32] Anita Sarma, Larry Maccherone, Patrick Wagstrom, and James Herbsleb. Tesseract: Interactive visual exploration of socio-technical relationships in software development. In *Proceedings of the 31st International Conference on Software Engineering*, ICSE '09, pages 23–33, Washington, DC, USA, 2009. IEEE Computer Society.

[33] Ben Shneiderman and Richard Mayer. Syntactic/semantic interactions in programmer behavior: A model and experimental results. *International Journal of Parallel Programming*, 8:219–238, 1979.

[34] Jonathan Sillito, Gail C. Murphy, and Kris De Volder. Asking and answering questions during a programming change task. *IEEE Trans. Softw. Eng.*, 34:434–451, July 2008.

[35] E. Soloway and K. Ehrlich. *Empirical studies of programming knowledge*, pages 507–521. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1986.

[36] Elliot Soloway, Robin Lampert, Stan Letovsky, David Littman, and Jeannine Pinto. Designing documentation to compensate for delocalized plans. *Commun. ACM*, 31:1259–1267, November 1988.

[37] Apache Solr - an open-source search server based on the Lucene Java search library. http://lucene.apache.org/solr/.

[38] M.-A. D. Storey, F. D. Fracchia, and H. A. Mueller. Cognitive design elements to support the construction of a mental model during software exploration. *J. Syst. Softw.*, 44:171–185, January 1999.

[39] Apache Subversion - enterprise-class centralized version control for the masses. http://subversion.apache.org/.

[40] Trac - project management and bug/issue tracking system. http://trac.edgewall.org/.

[41] Erik Trainer, Stephen Quirk, Cleidson de Souza, and David Redmiles. Bridging the gap between technical and social dependencies with ariadne. In *Proceedings of*

the 2005 OOPSLA workshop on Eclipse technology eXchange, eclipse '05, pages 26–30, New York, NY, USA, 2005. ACM.

[42] Davor ČubraniĆ, Gail C. Murphy, Janice Singer, and Kellogg S. Booth. Learning from project history: a case study for software development. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, CSCW '04, pages 82–91, New York, NY, USA, 2004. ACM.

[43] G. von Krogh, S. Spaeth, and K.R. Lakhani. Community, joining, and specialization in open source software innovation: a case study. *Research Policy*, 32(7):1217–1241, 2003.

[44] Anneliese von Mayrhauser and A. Marie Vans. Program comprehension during software maintenance and evolution. *Computer*, 28:44–55, August 1995.

[45] Xiaojun Wan, Jianwu Yang, and Jianguo Xiao. Towards a unified approach to document similarity search using manifold-ranking of blocks. *Inf. Process. Manage.*, 44:1032–1048, May 2008.

[46] Jianguo Wang and Anita Sarma. Which bug should i fix: helping new developers onboard a new project. In *Proceeding of the 4th international workshop on Cooperative and human aspects of software engineering*, CHASE '11, pages 76–79, New York, NY, USA, 2011. ACM.

[47] WordNet - a large lexical database of English synonyms. http://wordnet.princeton.edu/.

[48] Minghui Zhou and Audris Mockus. Developer fluency: achieving true mastery in software projects. In *Proceedings of the eighteenth ACM SIGSOFT international*

symposium on Foundations of software engineering, FSE '10, pages 137–146, New York, NY, USA, 2010. ACM.

[49] Justin Zobel and Alistair Moffat. Exploring the similarity space. *SIGIR Forum*, 32:18–34, April 1998.